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EXPERIMENTAL STUDIES ON INTERMITTENT AIRBLAST SPRAYS

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ABSTRACT

The atomisation of a liquid fuel by an air stream, in a continuous spray process depends on a number of factors; the most important being the relative velocity between the fuel and air and the flow ratio. The present study deals with the effect of these factors in intermittent airblast sprays.

The effect of the flow variables, air velocity, volume of air and volume of fuel and nozzle design on spray characteristics were studied. It is concluded from the results that for satisfactory atomisation of the fuel the air velocity should be about 700 f.p.s. and the flow ratio between 2,000—3,000 by volume. The influence of nozzle design on atomisation is indicated.

INTRODUCTION

The atomisation of a liquid fuel by an air stream in a continuous spray has been studied by Nukiyama and Tanasawa, Bitron and Lewis, *et. al.*,[1, 2, 3] and it has been established that the process depends on a number of factors the most important being the relative velocity between fuel and air and flow ratio*. The conclusions of Nukiyama and Tanasawa in relation to a continuous spray process (Figs. 1-3), could be expected to apply in some degree to an intermittent spray as well.

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* The ratio between the volume of fuel and volume of air.

The present study was undertaken in order to determine to what extent these effects would be modified under intermittent flow conditions for application in air blast injection systems of diesel engines and in particular pumpless injection systems under study in the Indian Institute of Science, Bangalore.

In a pumpless injection system the velocity of the airblast and the rate of air flow are interdependent and vary continuously during the injection process. Consequently a study of their relative effects on spray characteristics is rendered difficult. It was considered possible to circumvent this difficulty by studying the effect of each separately under simulated flow conditions. The data so obtained, although not directly applicable to a pumpless injection system would, however, indicate the general requirements to be satisfied in respect of air flow rates and velocities for obtaining good atomisation.

The aim of the investigation was therefore to study the following aspects of intermittent air blast sprays:

(i) effect of flow variables and nozzle geometry on spray characteristics and

(ii) spray formation and development.

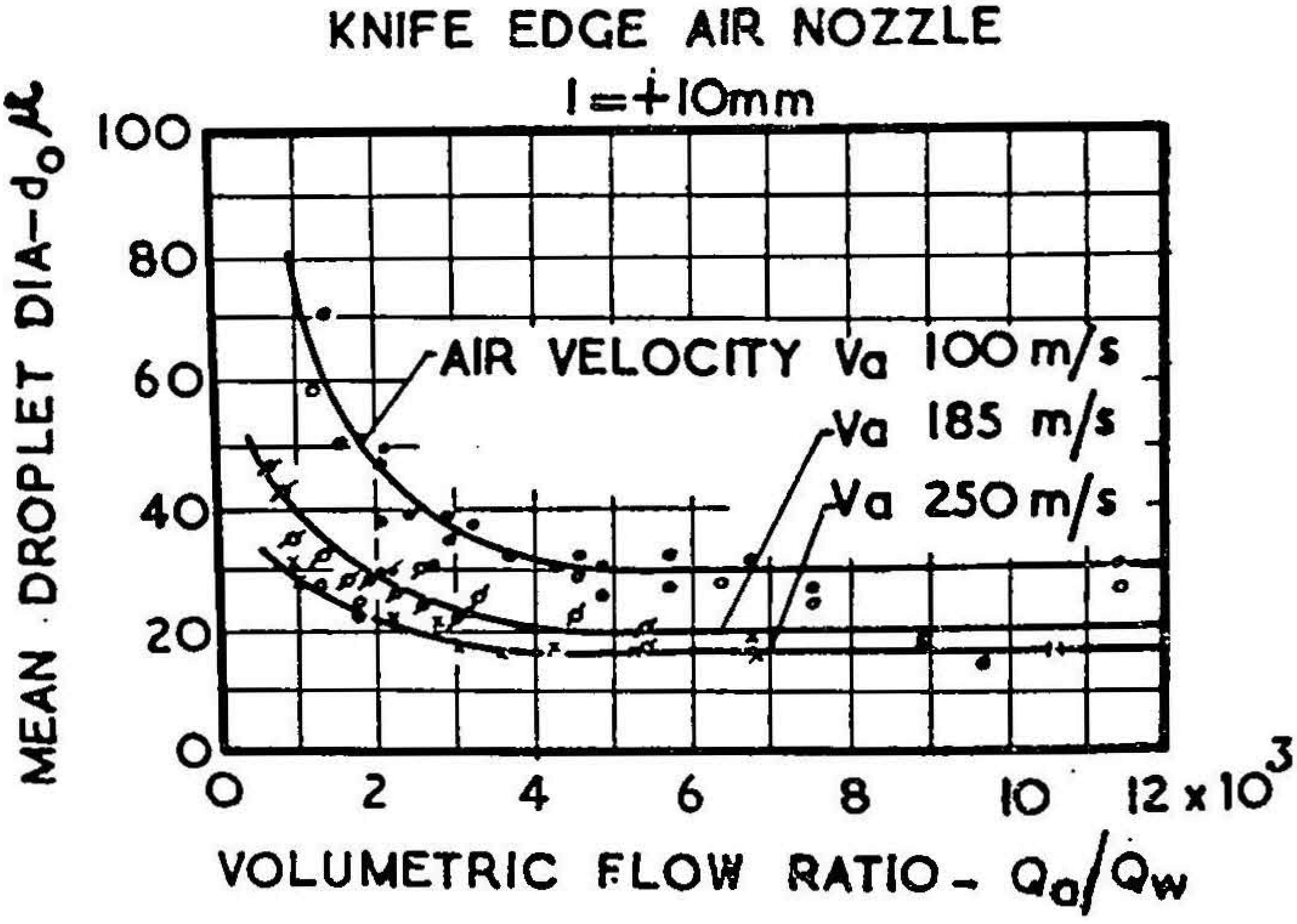

FIG. 1
Influence of Flow Ratio

TEST APPARATUS

A schematic drawing of the test apparatus is shown in Fig. 4. The apparatus consists of a rotary valve, a fuel pump, a nozzle or atomiser and a spray sampler.

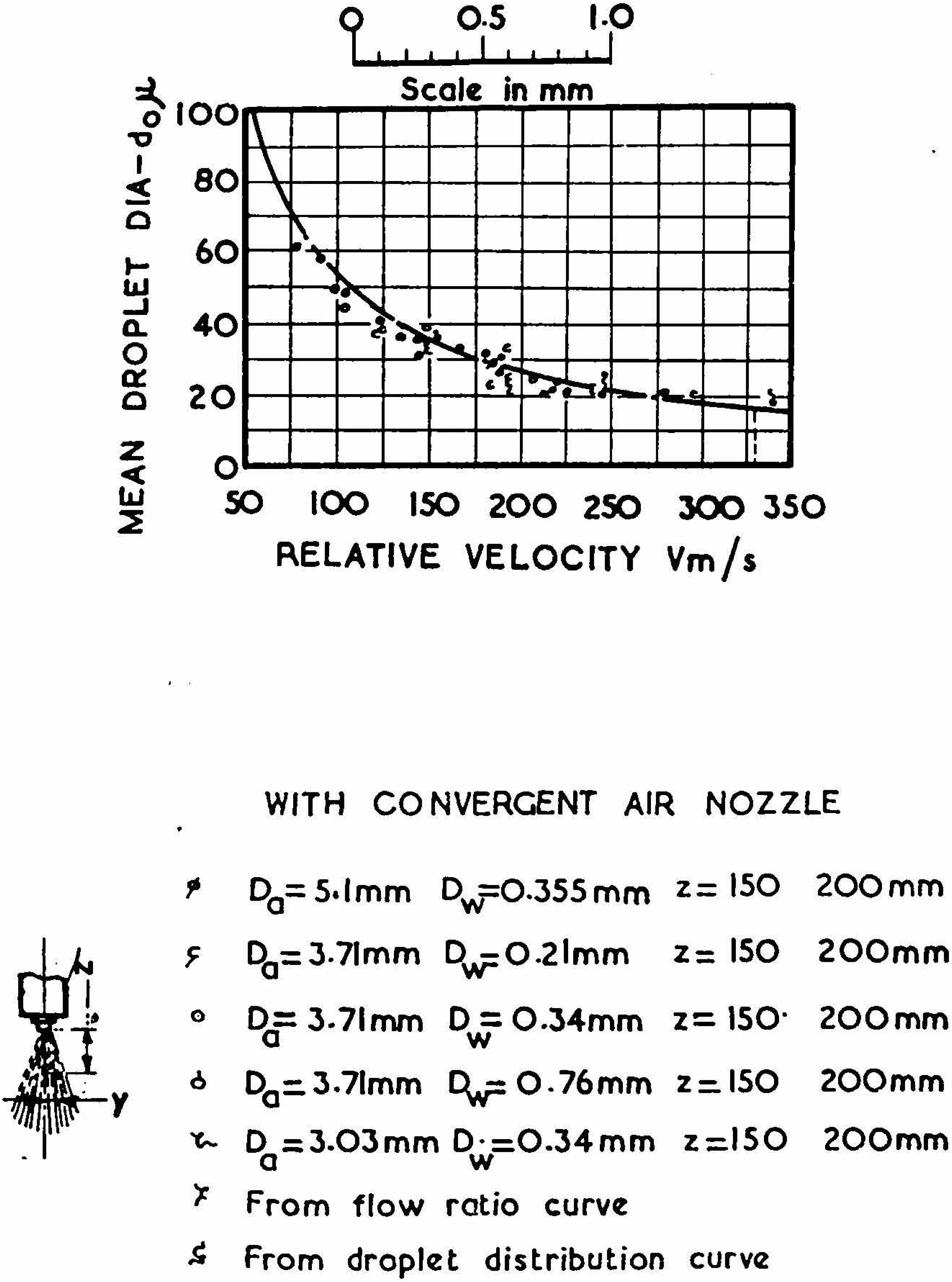

FIG. 2
Effect of Air Velocity

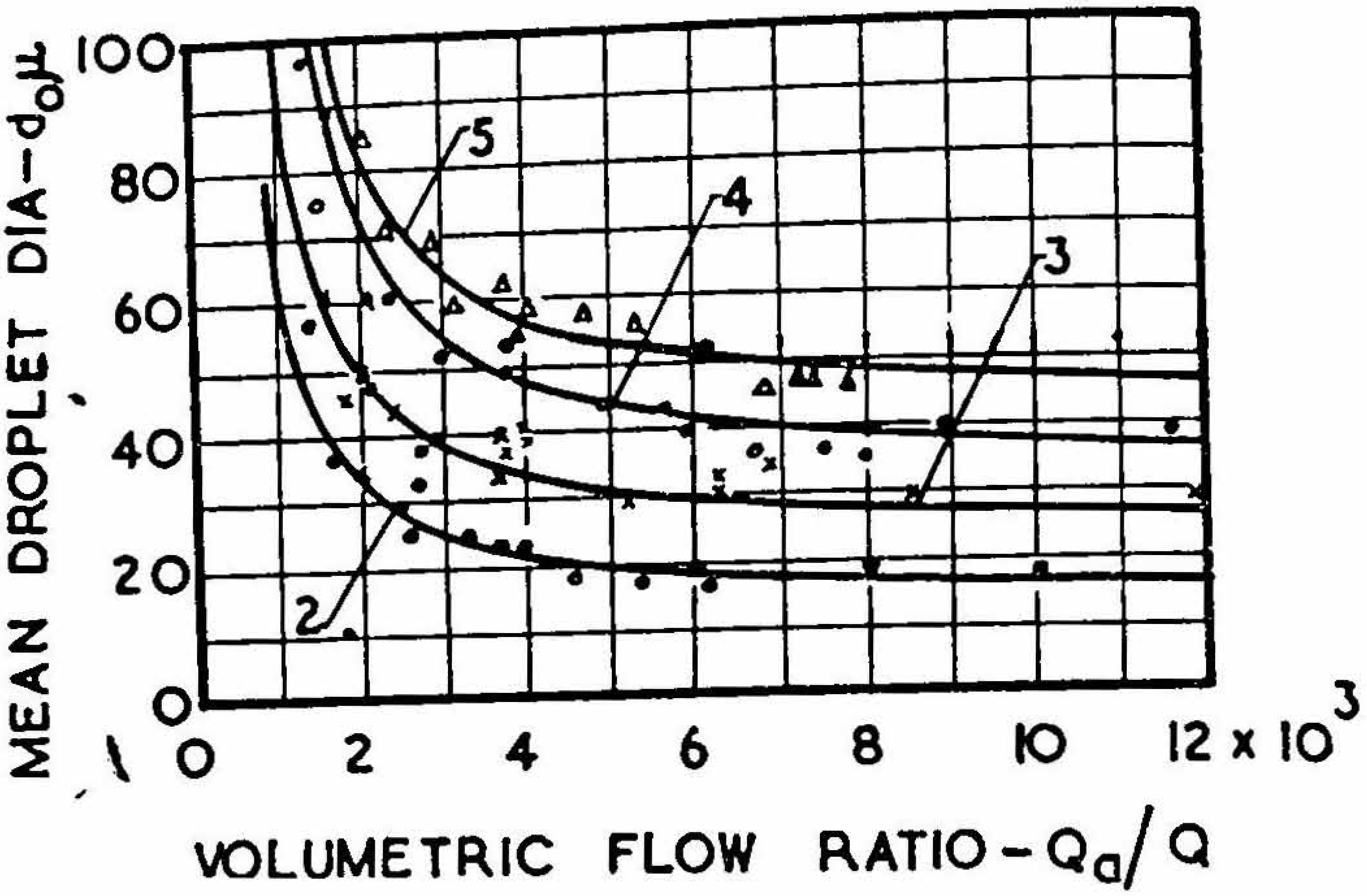

FIG. 3

Influence of Viscosity Surface Tension and Density

2. 40% glycerin ; water solution ; $\rho=1.102$ $\sigma=68.6$; $\mu=0.039$
3. 60% glycerin ; water solution ; $\rho=1.146$ $\sigma=66.7$; $\mu=0.081$
4. 75% glycerin ; water solution ; $\rho=1.180$ $\sigma=61.0$; $\mu=0.210$
5. 80% glycerin ; water solution ; $\rho=1.189$ $\sigma=61.4$; $\mu=0.252$

$v=3125$ m/s ; $D_1=0.34$ 0.66mm ; $D_a=4.05$mm

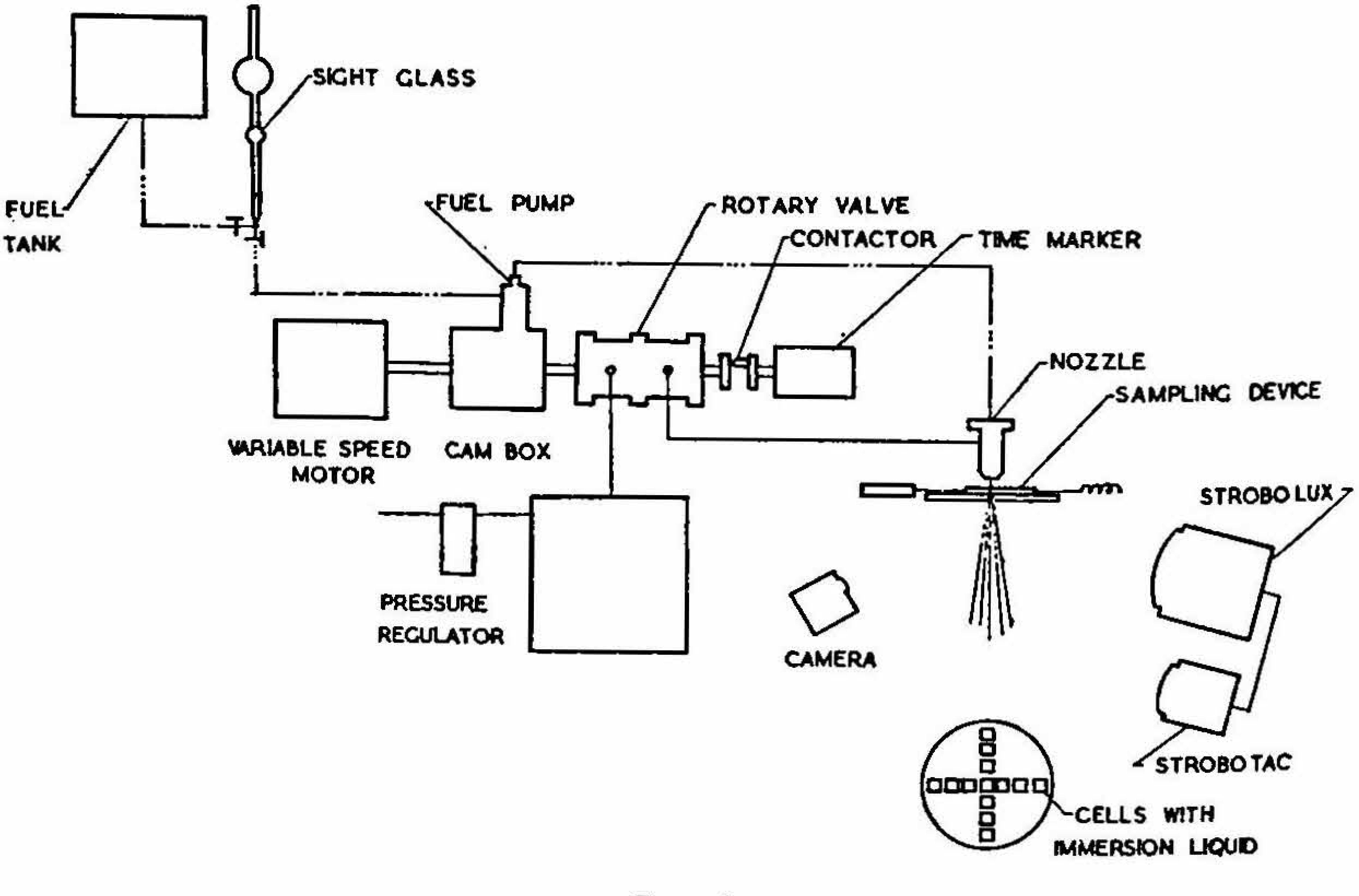

FIG. 4

Lay-out of Experimental Set-up

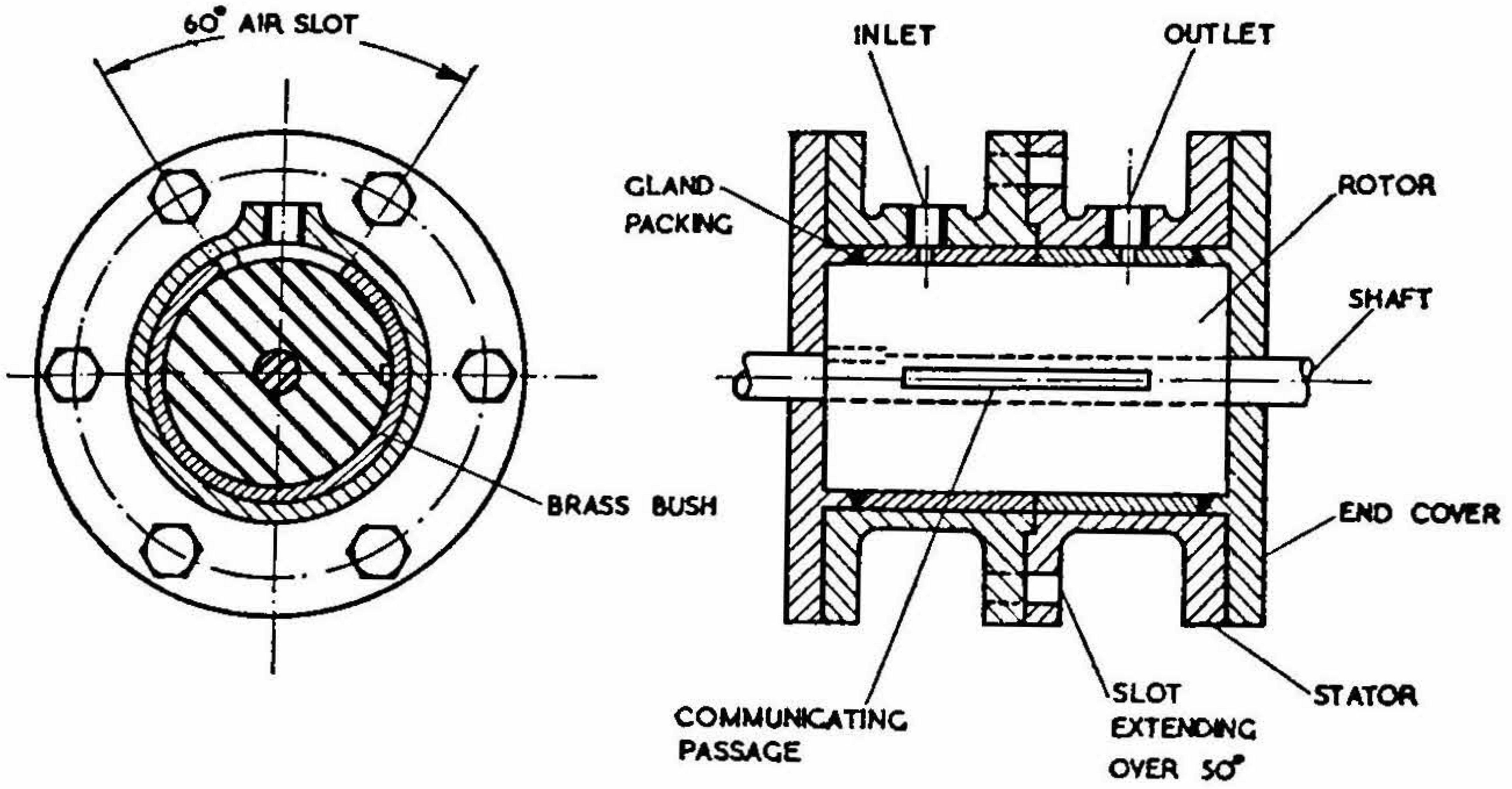

FIG. 5
Rotary Valve

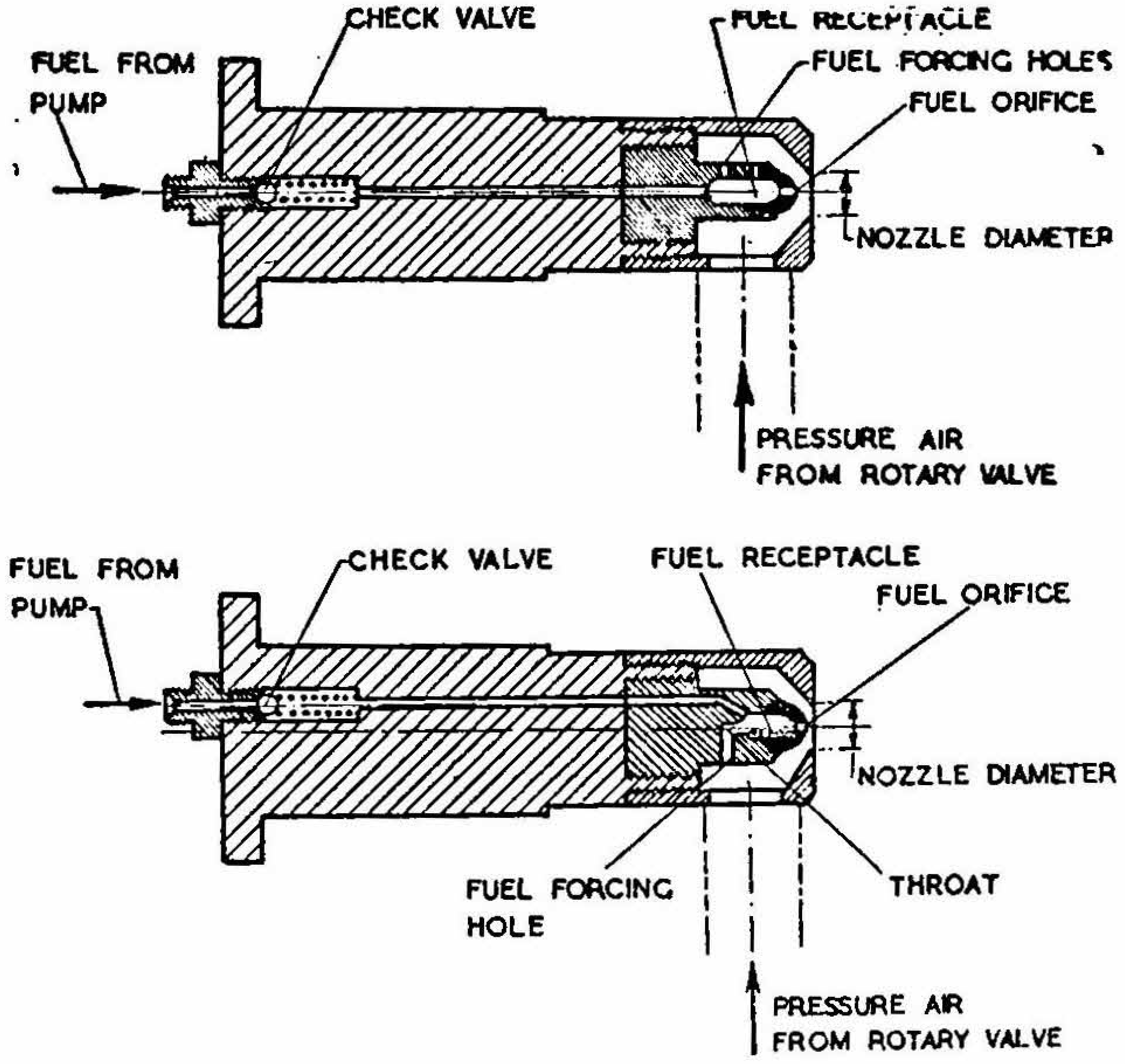

FIG. 6
Nozzle Design

Rotary Valve and Fuel Pump. The rotary valve and the fuel pump mounted on a common shaft, driven by an A.C. variable speed motor, regulate the supply of air and fuel respectively to the nozzle. Two sectional views of the rotary valve are shown in Fig. 5. The stator of the rotary valve is in two halves. Each half of the stator contains a brass bush with a slot extending over 60 degrees. The rotor has a groove on its surface which puts the slots in each half of the stator in communication with each other once every revolution. Air from the pressure vessel can then flow through the rotary valve to the nozzle. By turning one half of the stator relative to the other the period of air flow can be varied. A very close running clearance between the rotor and stator, limits the leakage between the inlet and outlet of the rotary valve to a low value. A conventional diesel injection pump is used for timing and metering of fuel, the fuel being delivered to the nozzle at a low pressure.

Nozzle Design. Nozzle designs tried out during the course of the investigation are shown in Fig. 6. Pressure air flowing through the nozzle at high

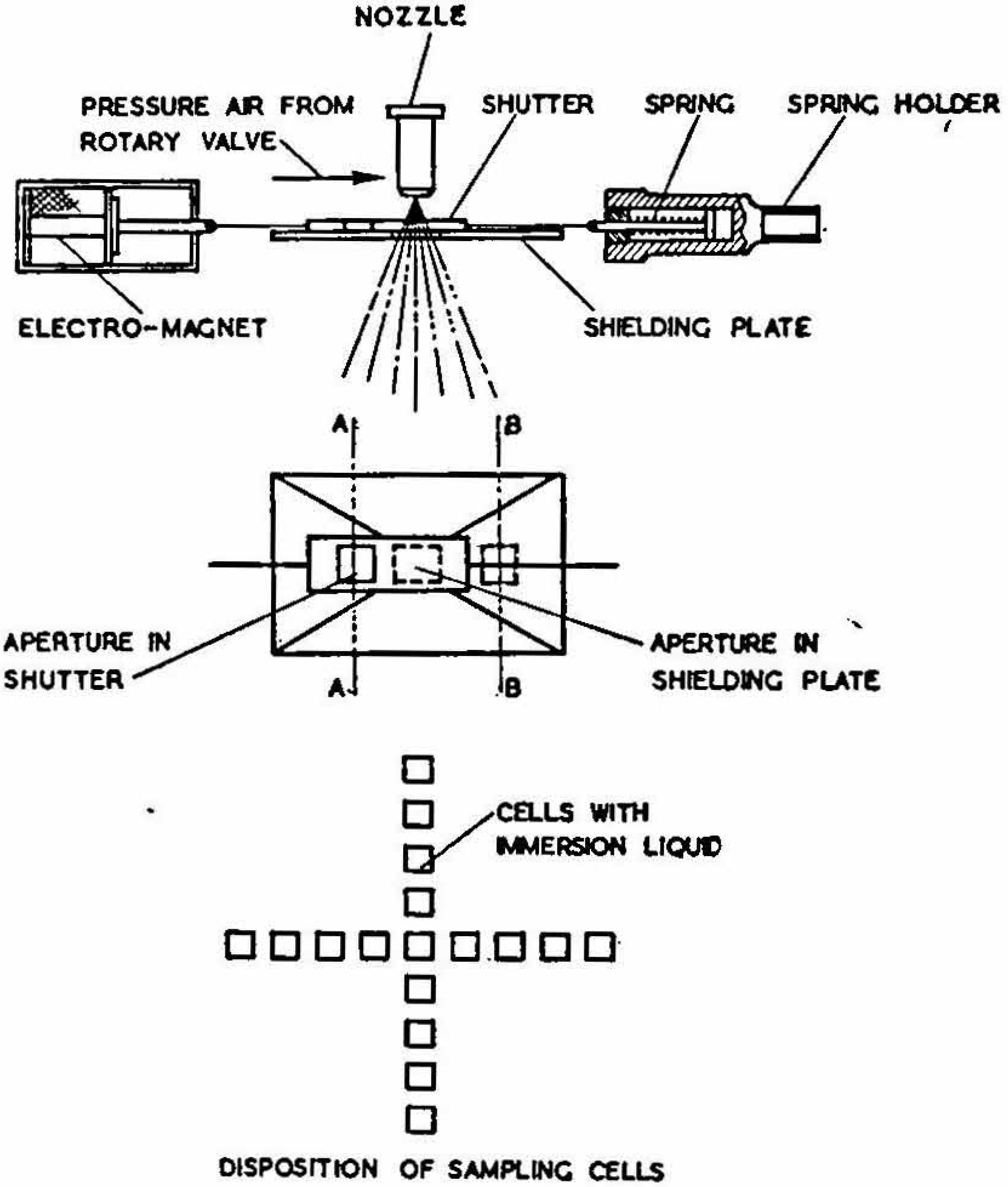

FIG. 7

Schematic Drawing of Sampler I

velocity carries the fuel and atomises it. The spray so produced is illuminated by a stroboflash for visual observation and photographing.

Spray Sampler. The spray sampler consists of a shutter with an aperture which is rapidly moved across the spray allowing only a part of the spray to pass through. Spray samples are collected at various points in the cross section of the spray so separated in small cells containing a suitable immersion liquid, for droplet size measurement. A high power microscope is used to measure the size of the droplets collected.

Two slightly different designs of samplers used in the experiments are shown in Fig. 7 and 8. An electromagnet holds the shutter in position AA against the spring force and can be switched off at any desired instant by means of a timed relay. The shutter then snaps back to position BB due to the spring force. As the shutter passes swiftly across the spray, the two apertures in the shielding plate and shutter register with each other for a very short period during which a small slice of the spray passes through and is collected in a number of cells containing the immersion liquid. By suitably timing the shutter, a slice of the spray during any part of the discharge period can be collected. By varying the shutter speed the fraction of the spray so separated is controlled.

The circuit of the timed relay used with the samplers is shown in Fig. 9. When a sample is desired to be collected the shutter is shielded from the spray and the contact points K_2 and K_3 are closed. The shutter is now drawn to the closed position against the spring force and the relay is ready to operate. The shield is removed and point K_1 is closed putting the circuit in operation. As soon as the circuit is completed by the contactor the solenoids are energised and K_2 and K_3 are tripped. The electromagnet being de-energised the shutter moves across the spray under the action of the spring force.

Photographic Arrangement. A schematic diagram of the arrangement for photographing the spray is shown in Fig. 10. The spray is illuminated by the strobolux working in conjunction with a stroboscope and a variable contactor. The rotating arm of the contactor touches the stationary contact once every revolution momentarily closing the circuit of the stroboscope and strobolux, producing a bright flash. The spray is illuminated at any desired instant by adjusting the position of the stationary contact.

A piezo electric pressure transducer was used in conjunction with a single beam Du Mont cathode ray oscilloscope to measure the pressure at the nozzle. A photocell was used to determine the shutter speed.

Fig. 11 is a photograph of the complete test-rig.

PRELIMINARY EXPERIMENTS

Preliminary experiments were carried out to calibrate the test nozzles for flow rates, to choose suitable immersion liquid for collecting the spray and to determine the optimum shutter speed for the spray sampler. The general pattern of distribution of the spray was also studied and this proved to be helpful in formulating the procedure followed in later experiments.

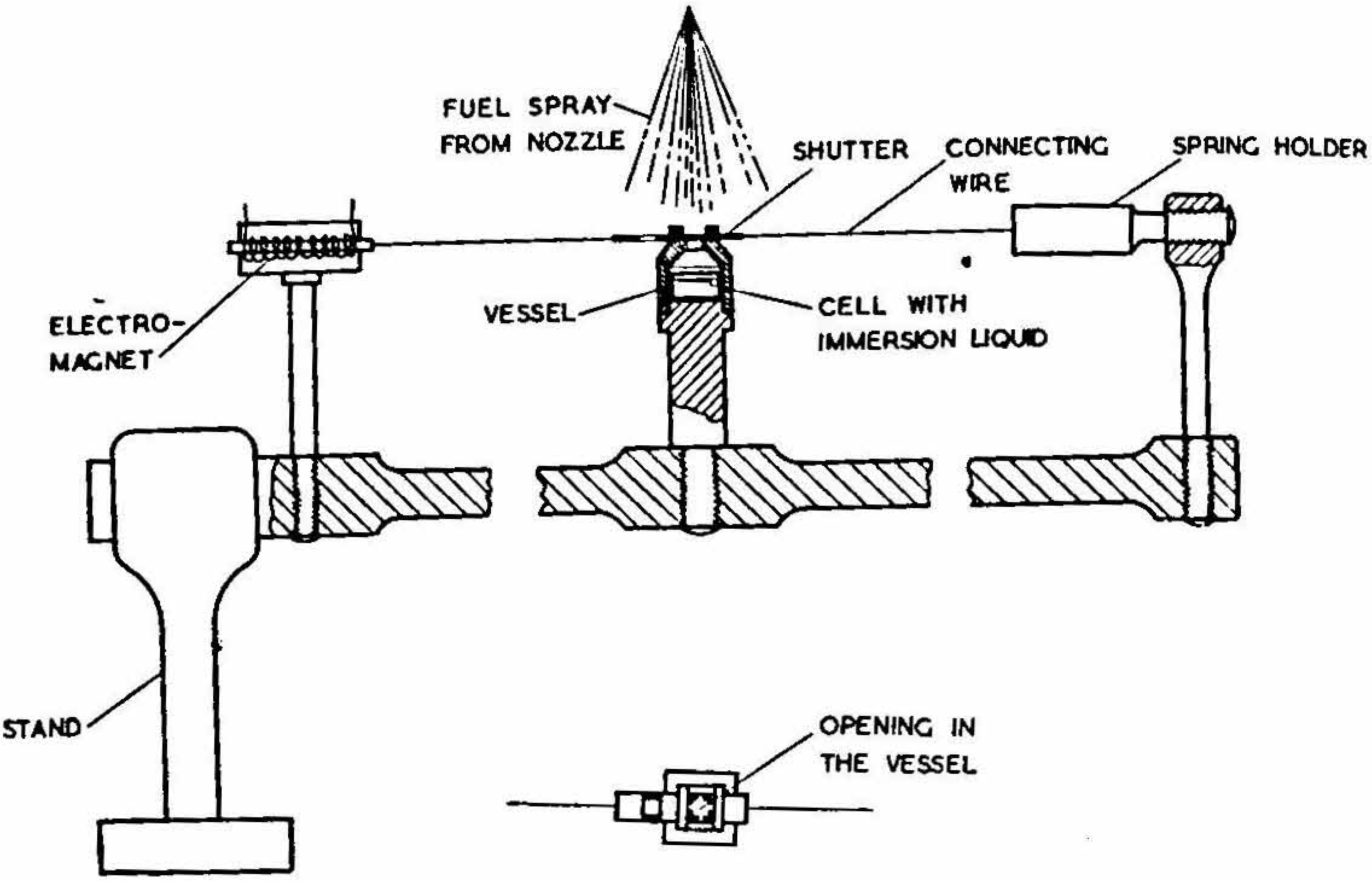

FIG. 8

Schematic Drawing of Sampler II

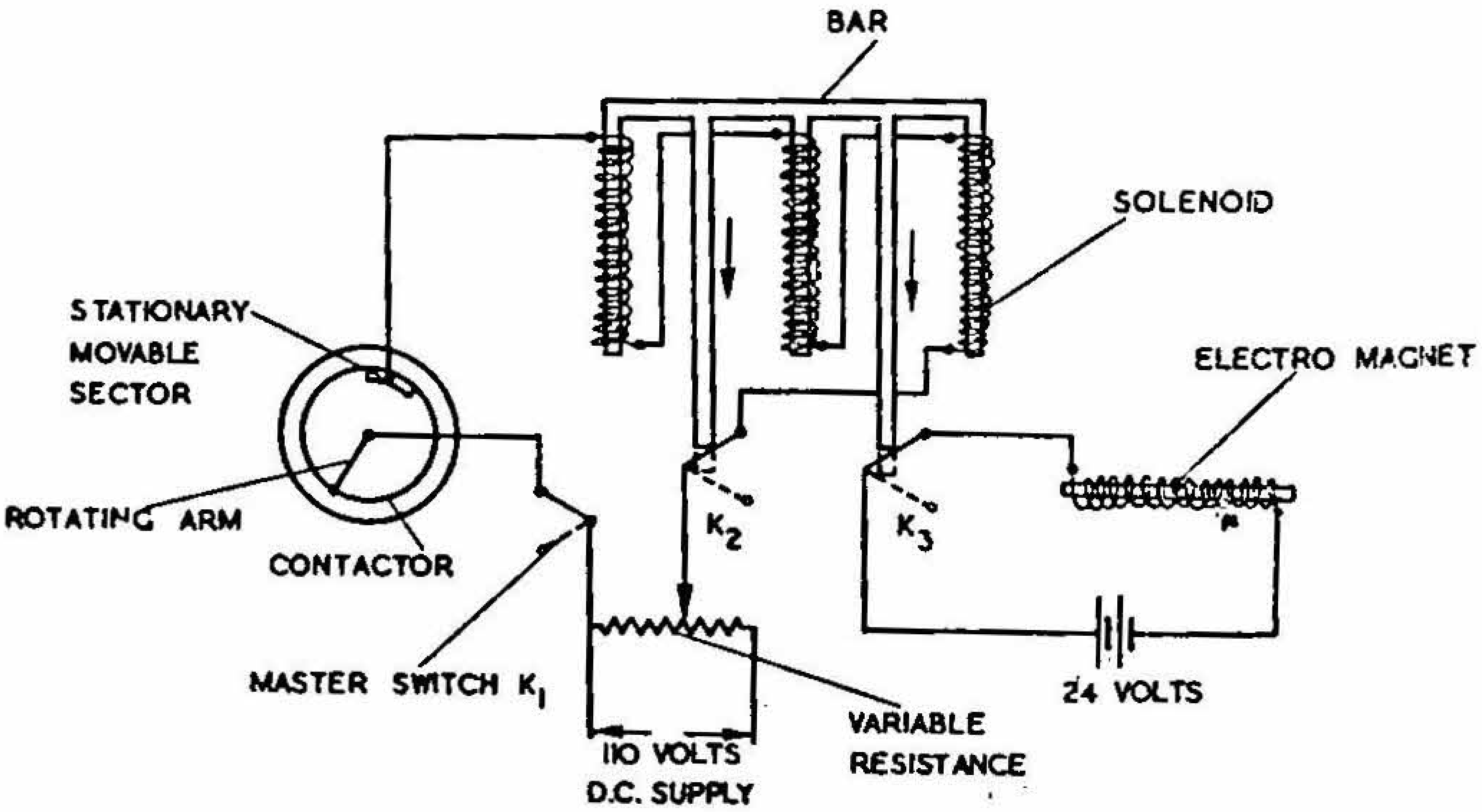

FIG. 9

Electrical Circuit of the Relay Employed in the Spray Samplers

Measurement of Air Flow. The air pressure at the nozzle was observed on the oscilloscope and was found to be practically constant over the period of injection. The following procedure was therefore adopted for measurement of air flow through the nozzles. The discharge from the nozzles was allowed into an air box connected to a standard gas meter. The volume of the air box was made sufficiently large to damp out pressure fluctuations. The rate of air flow through each test nozzle was determined at various pressures. Air flow Vs pressure curves for the test nozzles are shown in Fig. 12.

Choice of immersion liquid. The requirements of a good immersion liquid according to Rupe[4] are:

(1) The liquid must be absolutely immiscible with the fuel injected,

(2) the difference in density between the immersion liquid and fuel should be as small as possible so that the droplets approach a common plane for photographing,

(3) the viscosity of the liquid must be low enough for the droplets to penetrate the liquid without breaking up and yet high enough to restrict convection and prevent movement and subsequent coalescence,

(4) surface tension of the liquid must be low in order to allow the small droplets to penetrate the surface,

(5) the vapour pressure of the liquid should be low enough to prevent the formation of bubbles inside the cell before photographs are taken and

(6) the liquid must have good light transmission characteristics, be non-toxic and as nearly chemically inert as possible.

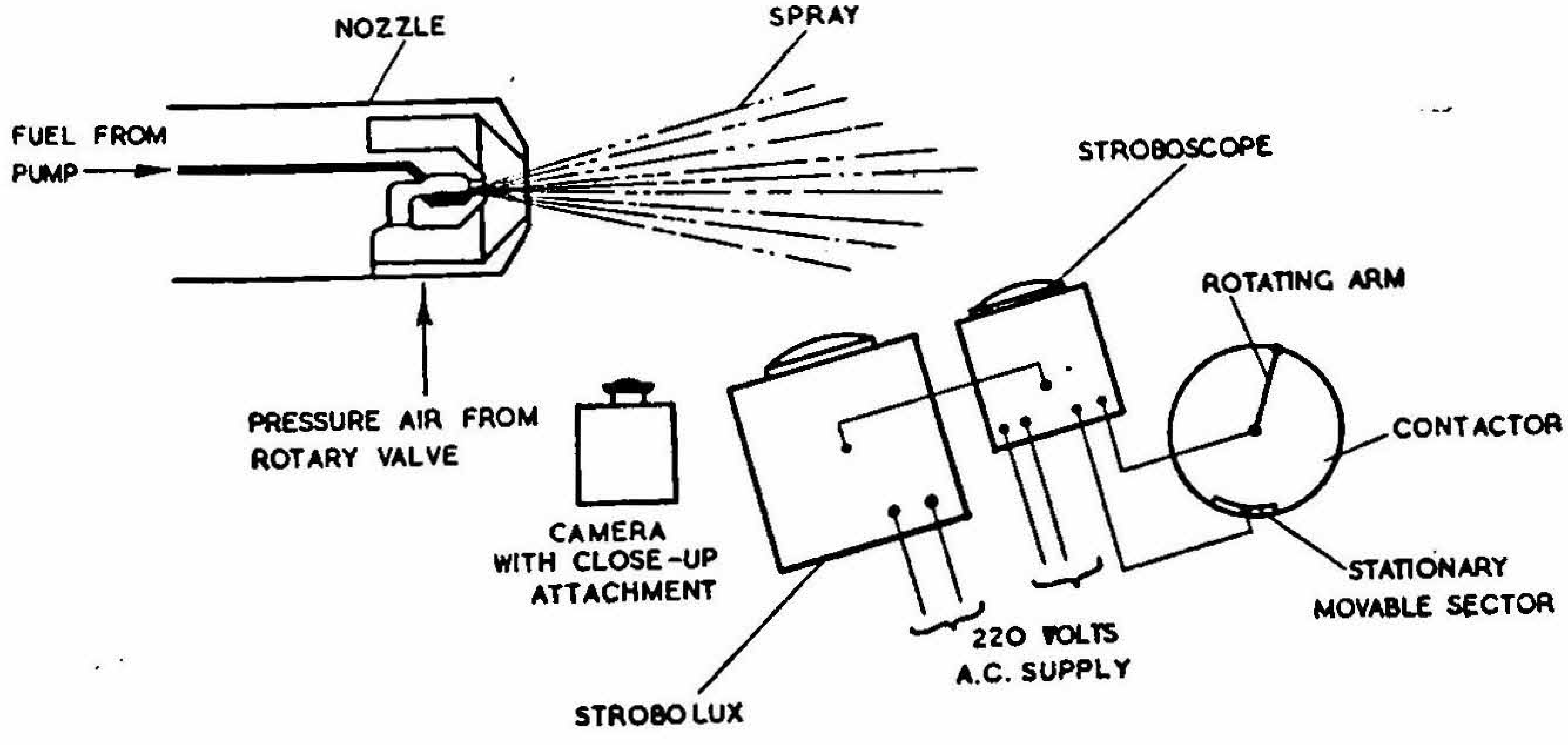

FIG. 10

Schematic Diagram of Photographic Arrangement

Paraffin, lubricating oil and other mineral oils were considered unsuitable as immersion media as they would mix readily with the fuel* under study. Glycerine, mixtures of glycerine and water in different proportions, castor oil, gelatine, gelatine-water mixtures in different proportions and silicone fluid F 110/300 were therefore tried out to ascertain their suitability. Silicone Fluid F 110/300 was found to be the best medium fulfilling most of the requirements of a good immersion liquid. Typical droplet photographs obtained with immersion liquid are shown in Fig. 13. Table 1 gives the properties of silicone F 110/300.

TABLE 1

Properties of Silicone Fluid F 110/300.

1. Density.	0.9741 gm/cc 27.5°C (Density of light diesel oil : 0.895 gm/cc at 27.5°C).
2. Viscosity.	367 C.S. at 27.5 °C (Viscosity of light diesel oil 10.9 C.S. at 27.5°C).
3. Surface Tension.	19.75 dynes/cm at 27°C. (Surface Tension of light diesel : 27 dynes/cm at 27°C).
4. Immiscible with light diesel oil.	
5. Chemically inert.	
6. Colourless.	

Determination of Optimum Shutter Speed. The shutter speed of the samplers was determined in the following manner :

A photocell was fixed underneath the shutter and shieded from extraneous light falling on it as shown in Fig. 14. When the sampler was operated, light would fall on the photocell during the period the shutter aperture and the opening in the shielding plate were in line, producing a trace on the oscilloscope. The trace was photographed and the period during which the shutter is open was determined by superimposing on it a known frequency supplied from a signal generator.

The effect of shutter speed on droplet size was determined by varying the the shutter speed from 0.0067 to 0.0134 sec., for sampler I and from 0.005 to 0.01 sec., for sampler II. From an examination of the curves relating shutter speed and droplet size for the two samplers (Figs. 15, 16), optimum shutter speeds of 0.0067 sec. and 0.005 sec., respectively, were fixed for samplers I and II. In both the samplers the maximum size of aperture possible was used to minimise 'edge effects'.

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* Light Diesel Oil.

Study of Spray Distribution. Sampler 1 gives a fair indication of the spatial distribution of the droplets in addition to the droplet size. Results of the experiments conducted to determine the optimum shutter speed for sampler I indicated that the central part of the spray is coarse and that the spray gets progressively finer towards the periphery. It was also observed that the variation of mean droplet size along any radius was similar. Further experiments were conducted to determine the effect of air velocity and flow ratio on the distribution pattern. The results shown in Fig. 17 indicate there are three regions in which the droplet size is fairly constant.

Experiments conducted to study the variation of droplet size over the discharge period indicated that the degree of atomisation over the entire period of the spray is substantially uniform. Hence for convenience, the sampling procedure adopted in experiments to follow was to take only three samples, one from each of the three regions of uniform atomisation during the middle phase of the discharge period.

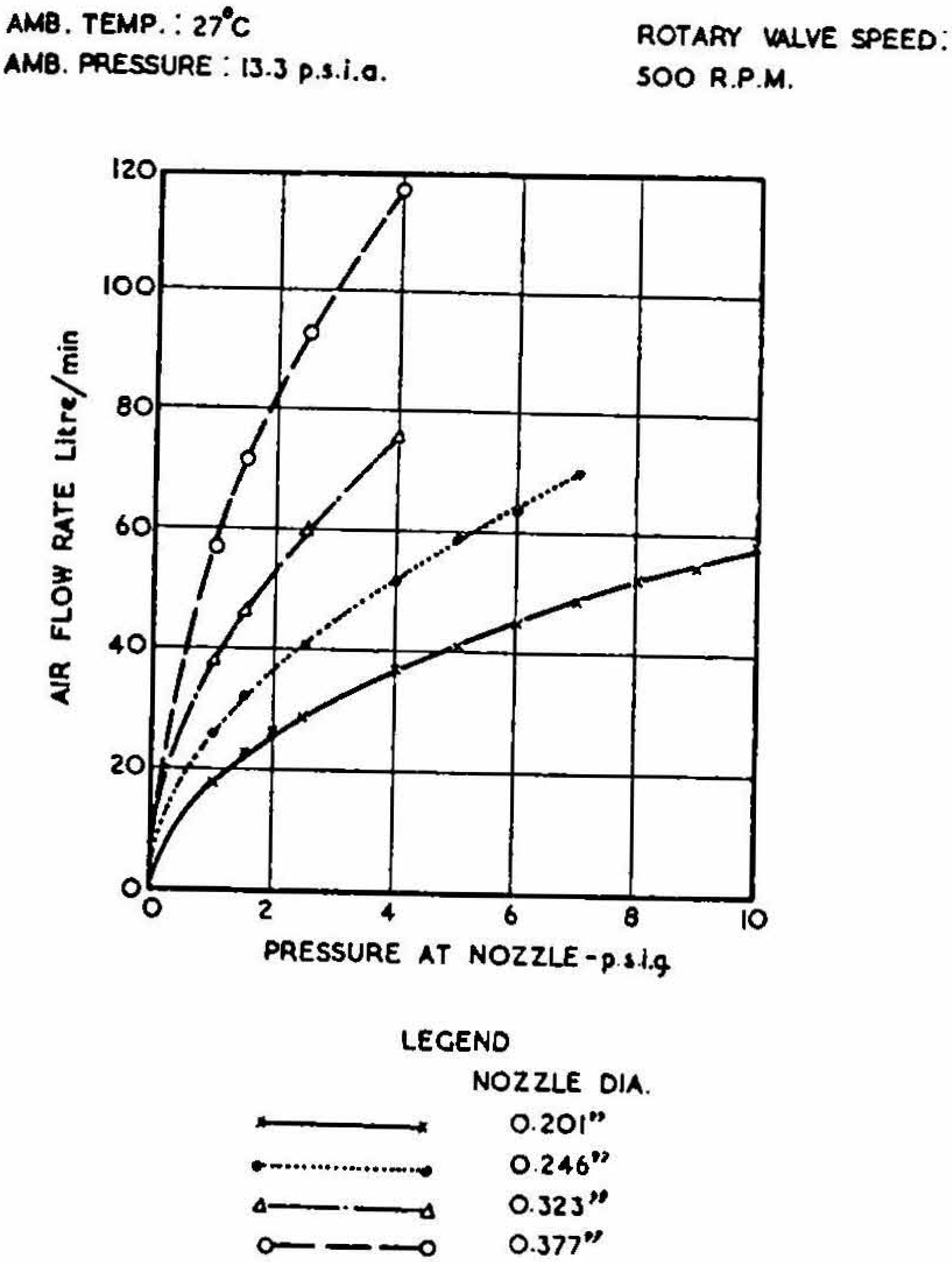


FIG. 12

Pressure *Vs* Air Flow for the Test Nozzles

EXPERIMENTS TO STUDY THE EFFECT OF FLOW VARIABLES AND NOZZLE GEOMETRY ON SPRAY CHARACTERISTICS

The effect of the flow variables namely air velocity, volume of fuel and volume of air as also the effect of fuel orifice diameter and nozzle diameter on spray characteristics such as cone angle, penetration, and mean droplet size was studied by varying one of the variables at a time keeping the remaining constant.

Spray Cone Angle. The cone angle of the spray was determined by photographing the spray using single flash photographic technique. The results of experiments on the effect of the variables involved on the spray cone angle are shown in Figs. 18-21. It is clear from these that the orifice diameter and air velocity are the only two variables that affect the cone angle significantly.

To obtain the cone angle for a given fuel orifice diameter and any air velocity, the spray cone angle was measured over the entire range of fuel orifice diameters at different air velocities. It is seen from Fig. 22 that for a given air velocity the cone angle increases as the orifice diameter increases upto a value of 0.032 in, and remains constant thereafter. The cone angle decreases as the velocity increases,

Spray Penetration. The spray was illuminated by a flash from a strobolux triggered by a contactor on a pump shaft and the phasing of the flash in relation to the injection cycle was varied manually under running conditions. The movement of the spray was observed over its entire length at 2 inch intervals and the crank angles corresponding to the contactor positions were

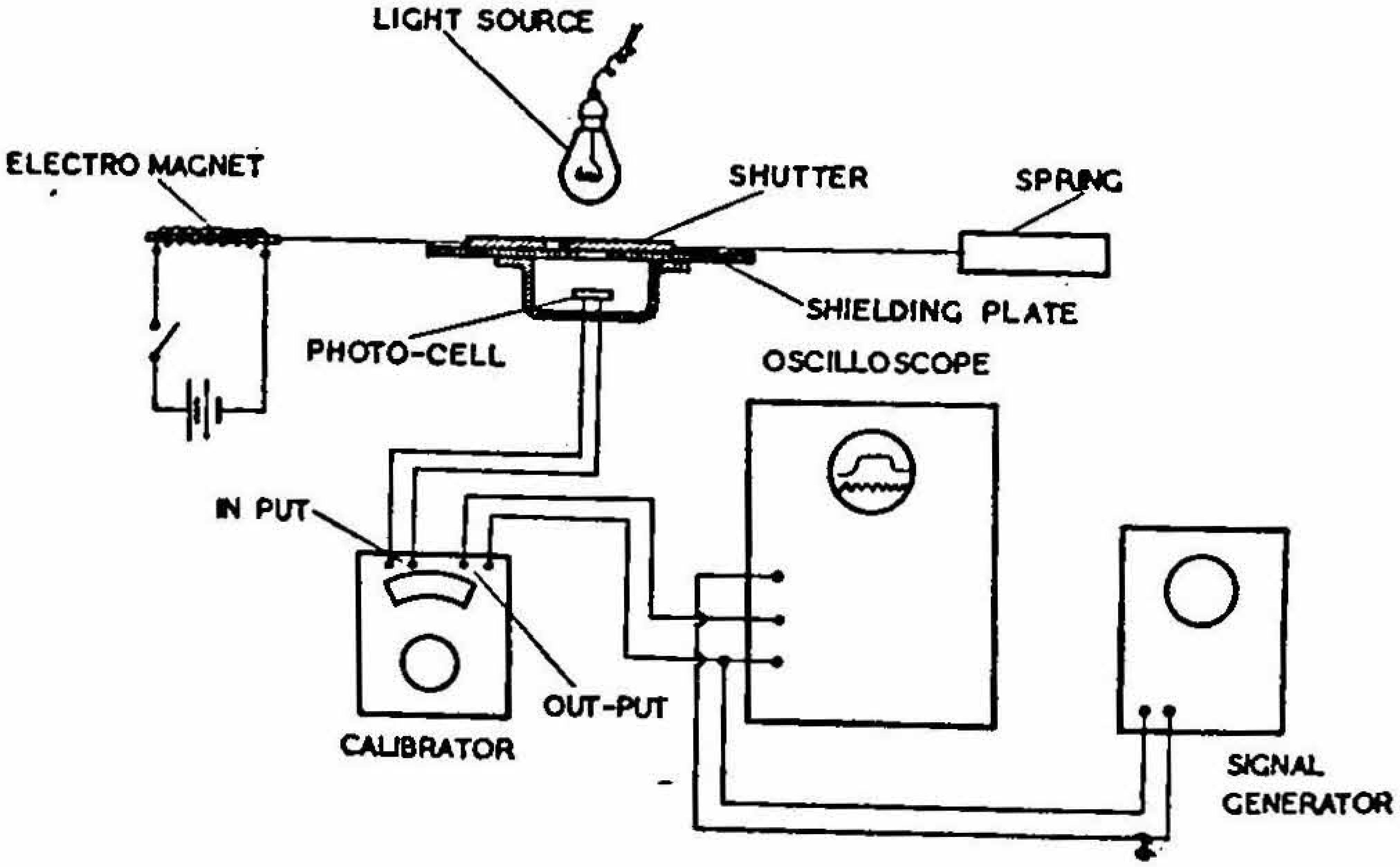


FIG. 14

Measurement of Shutter Speed

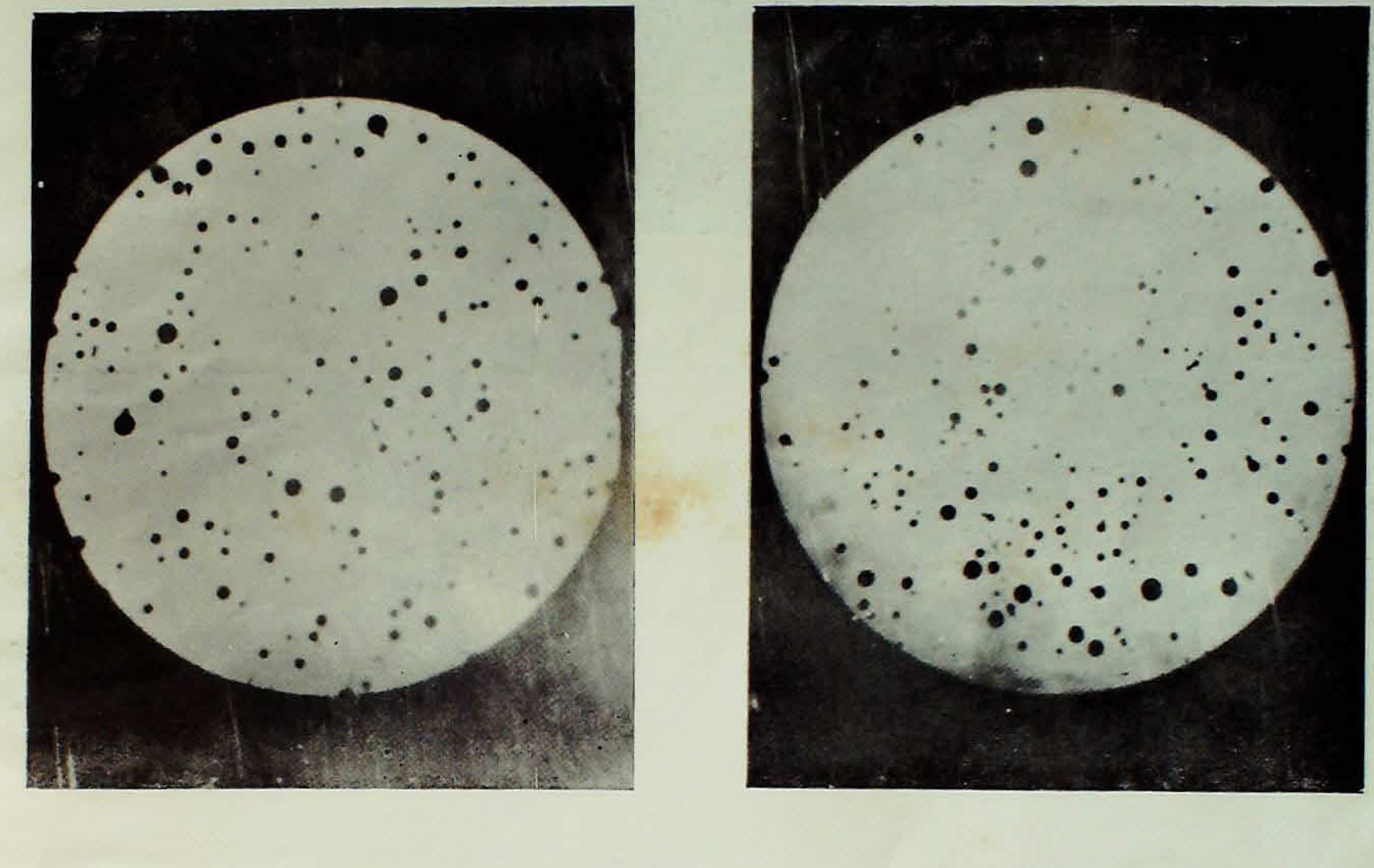
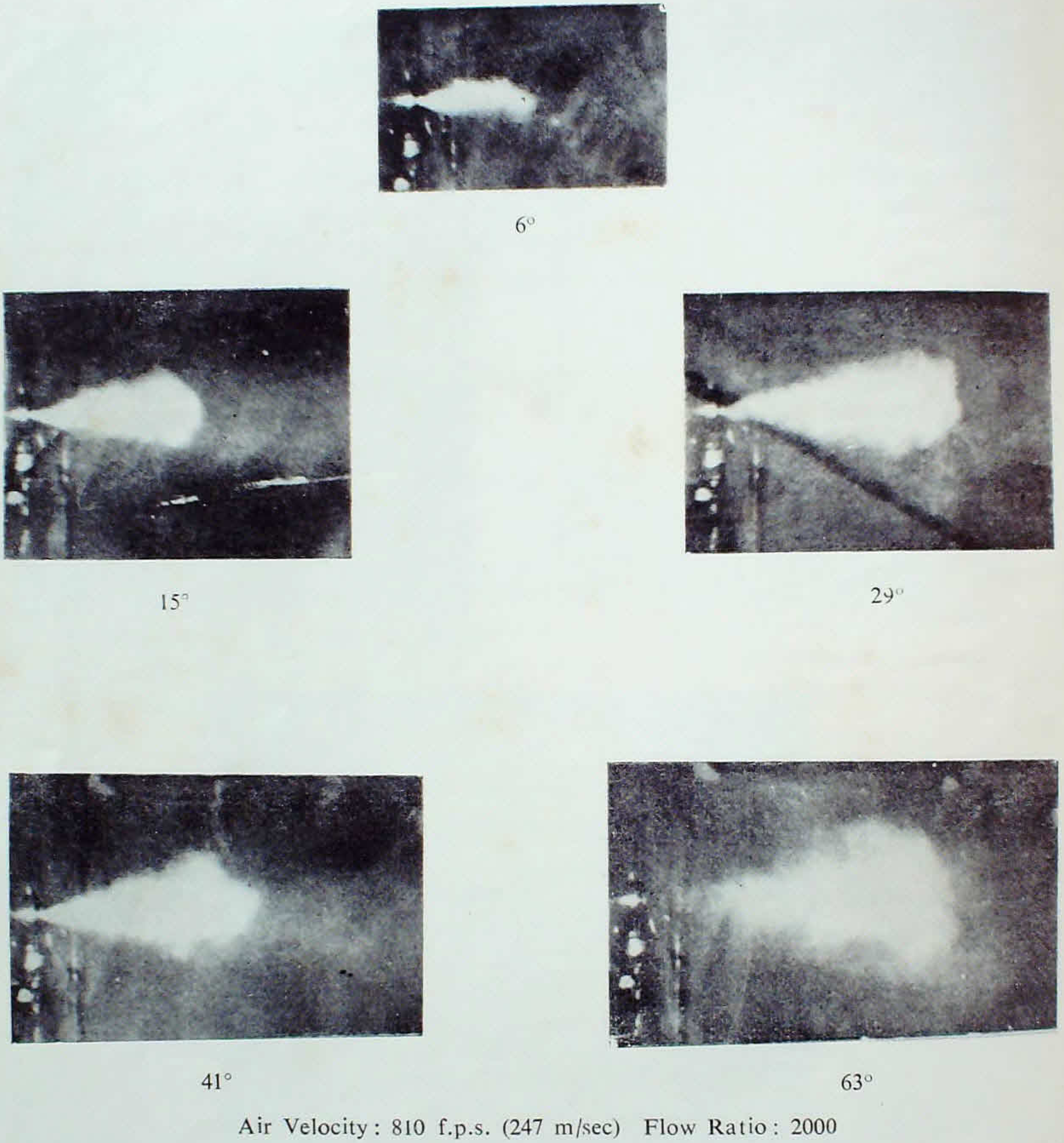


FIG. 13

Typical Droplet Photographs with Silicone Fluid F110/300
(Magnification : 60)



6°

15°

29°

41°

63°

Air Velocity: 810 f.p.s. (247 m/sec) Flow Ratio: 2000

Fig. 31

Formation of Spray
(No. indicates degrees after beginning of injection)

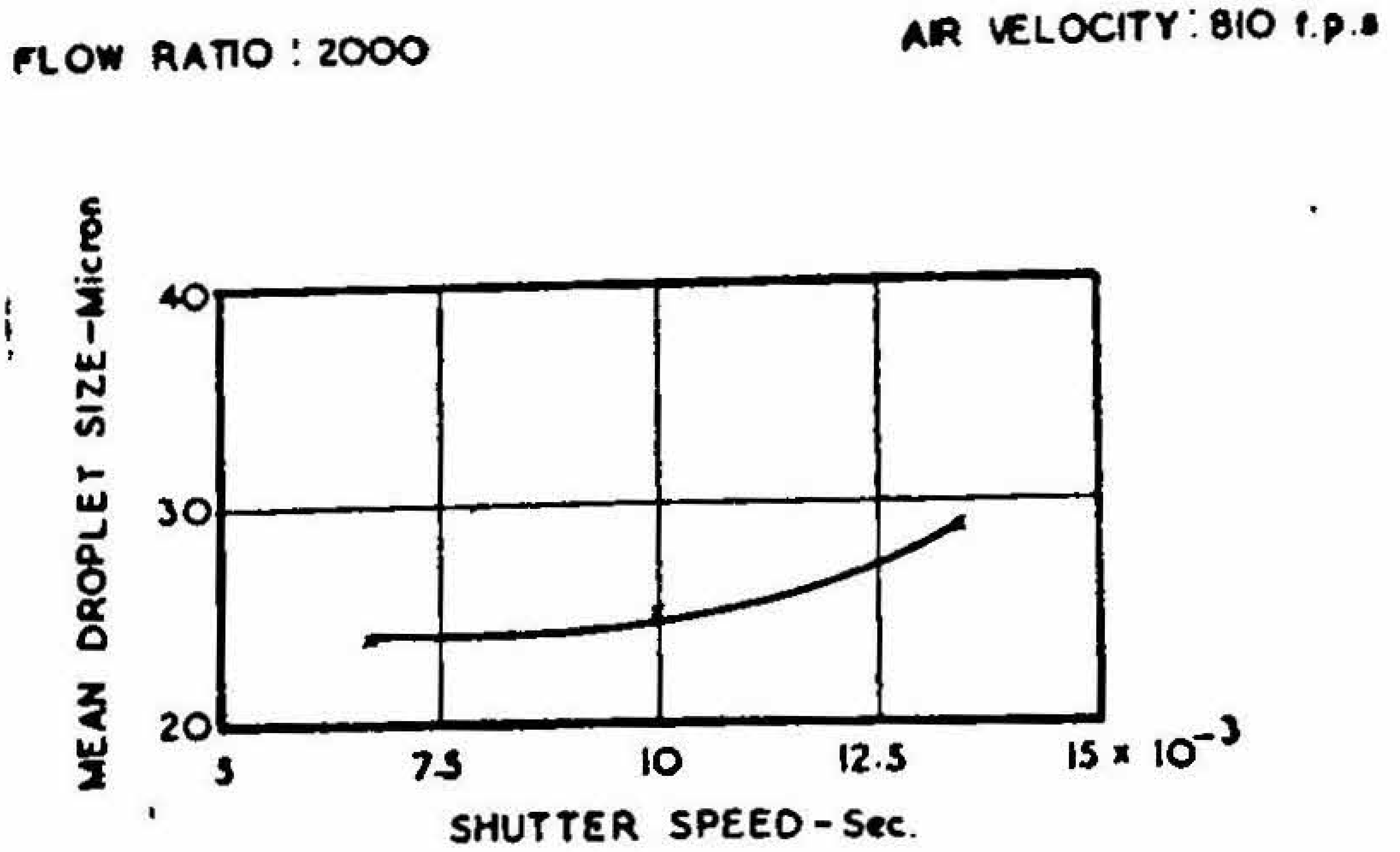


FIG. 15

Effect of shutter speed on droplet size Sampler I

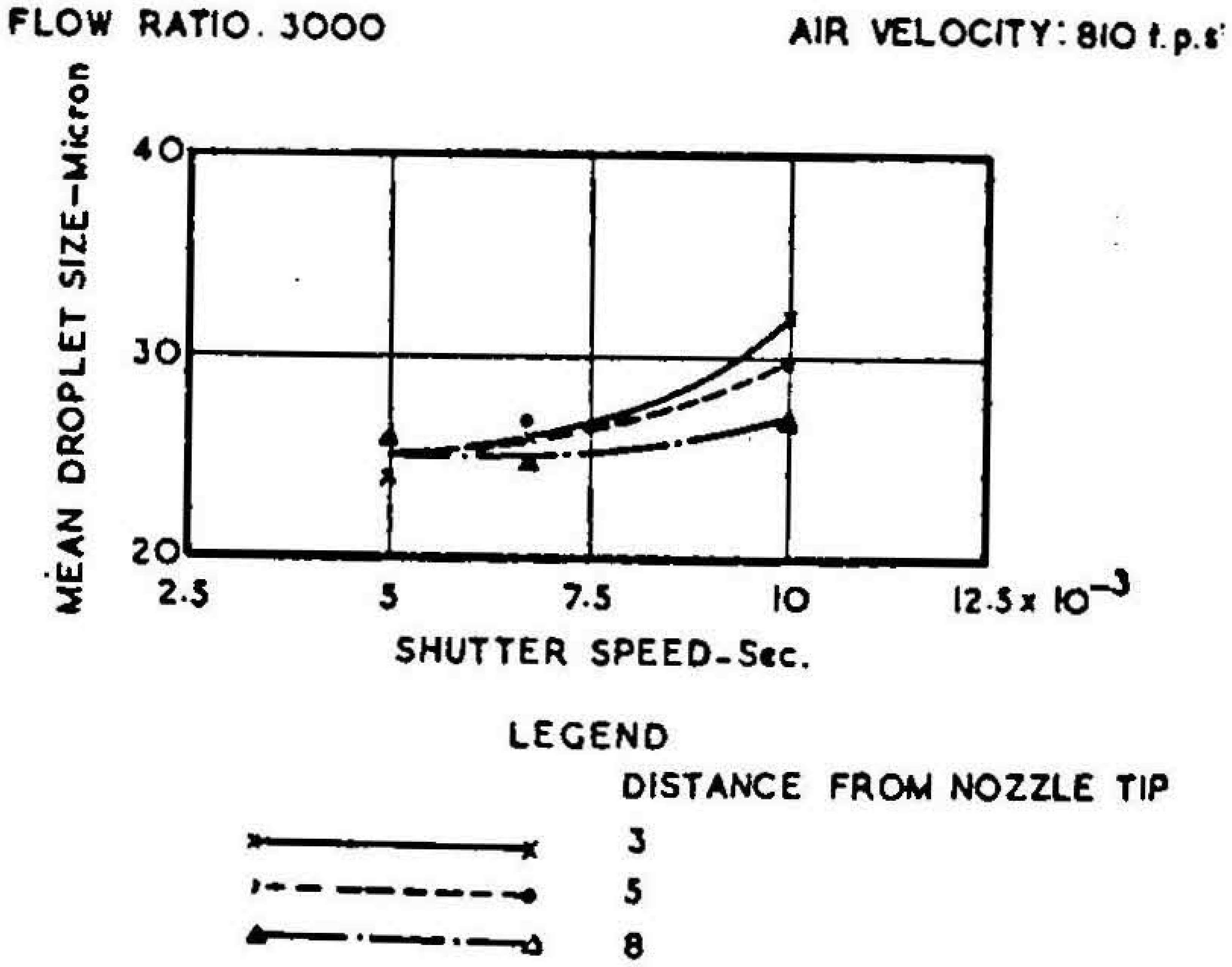


FIG. 16

Effect of shutter speed on droplet size Sampler II

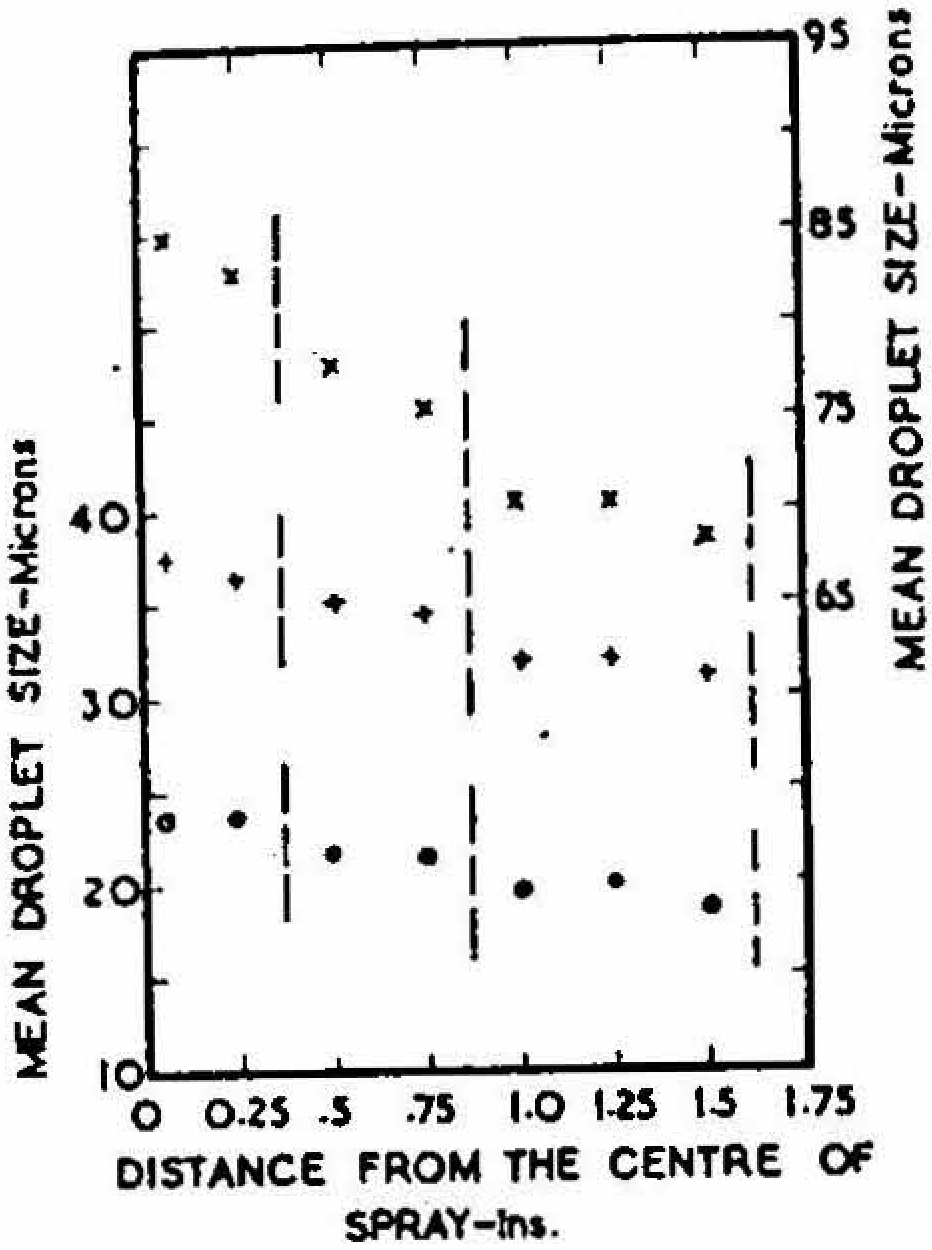


FIG. 17
Spray Distribution

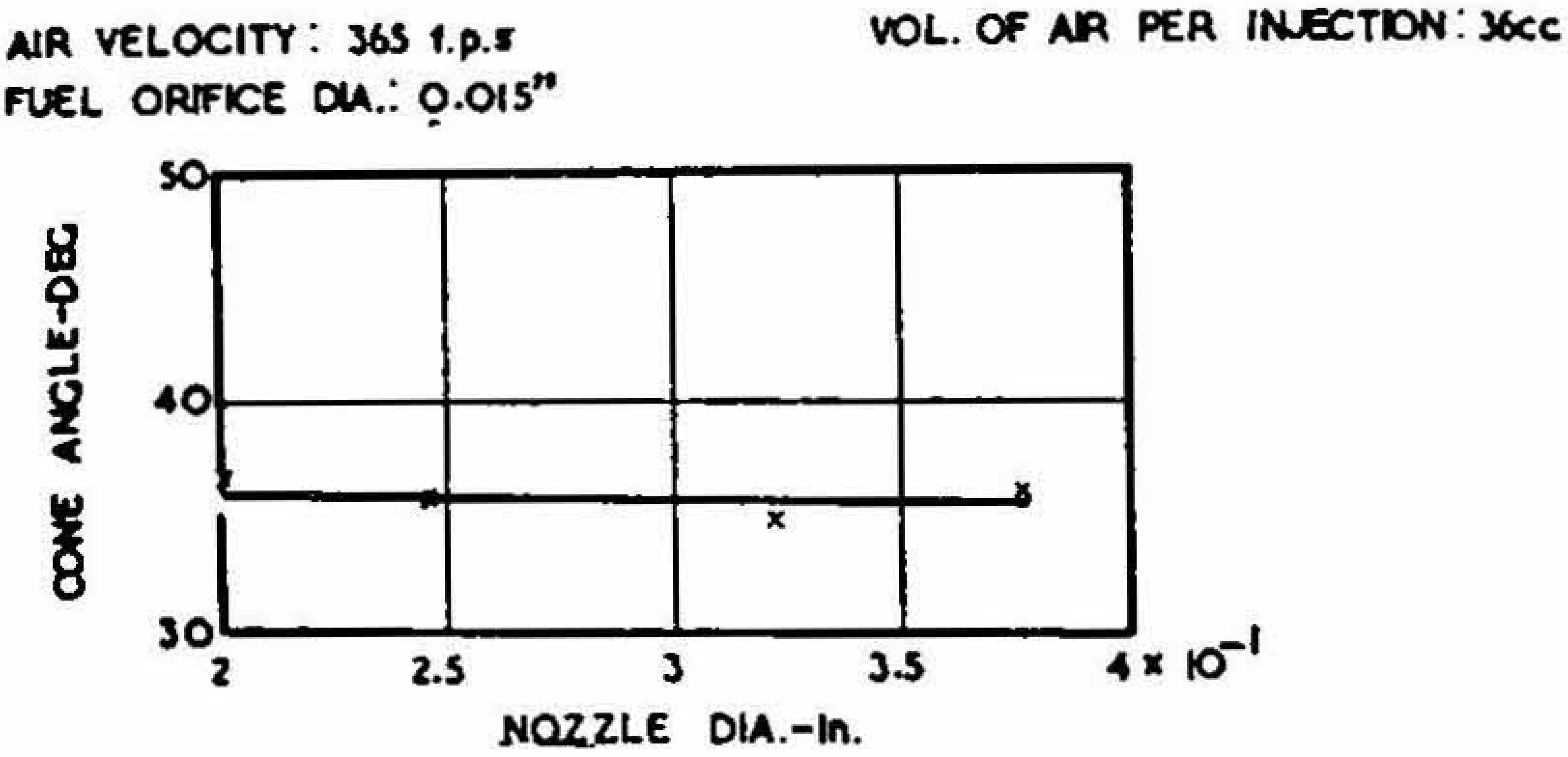


FIG. 18
Effect of Nozzle Diameter on SprayCone Angle

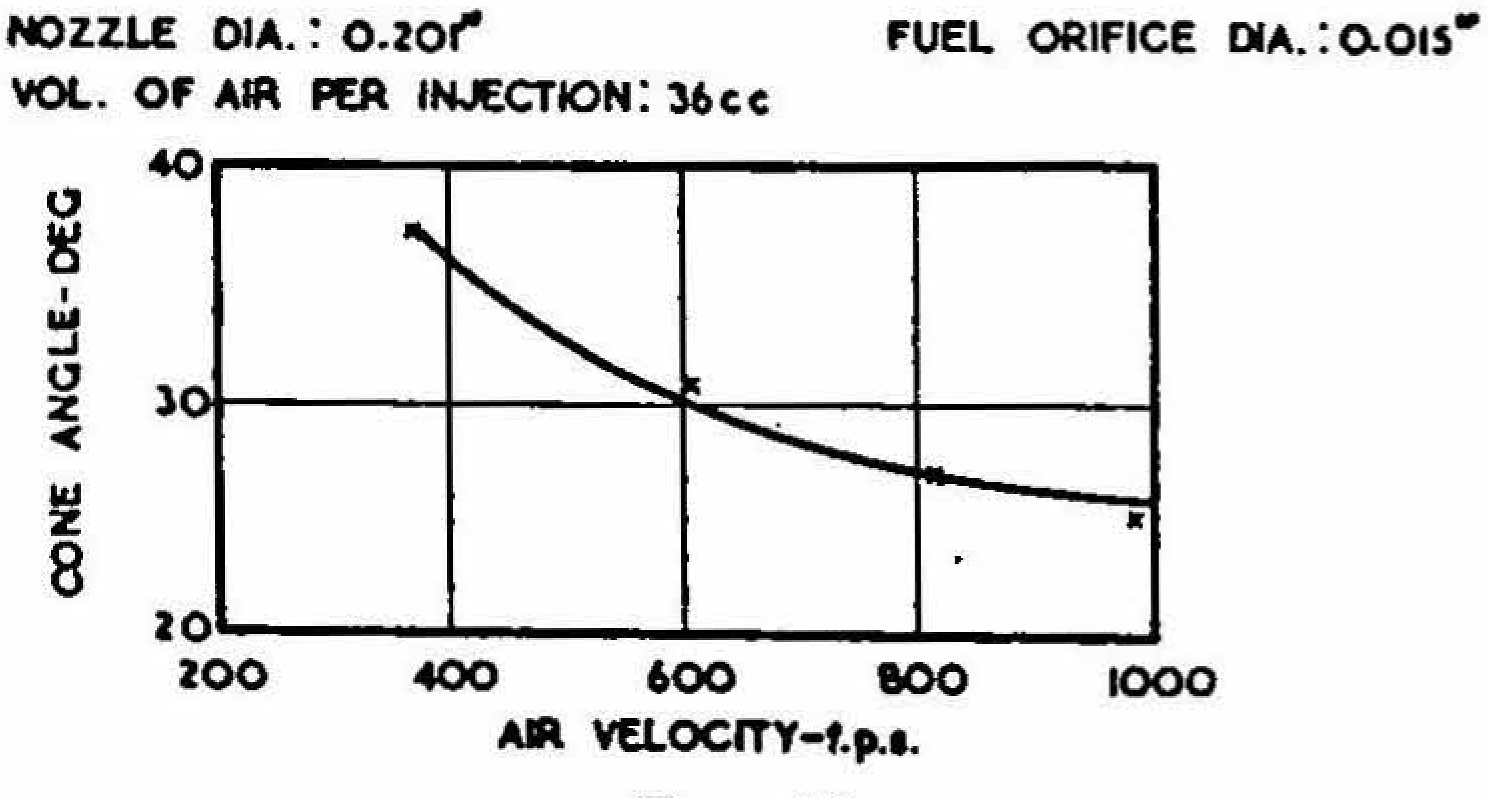
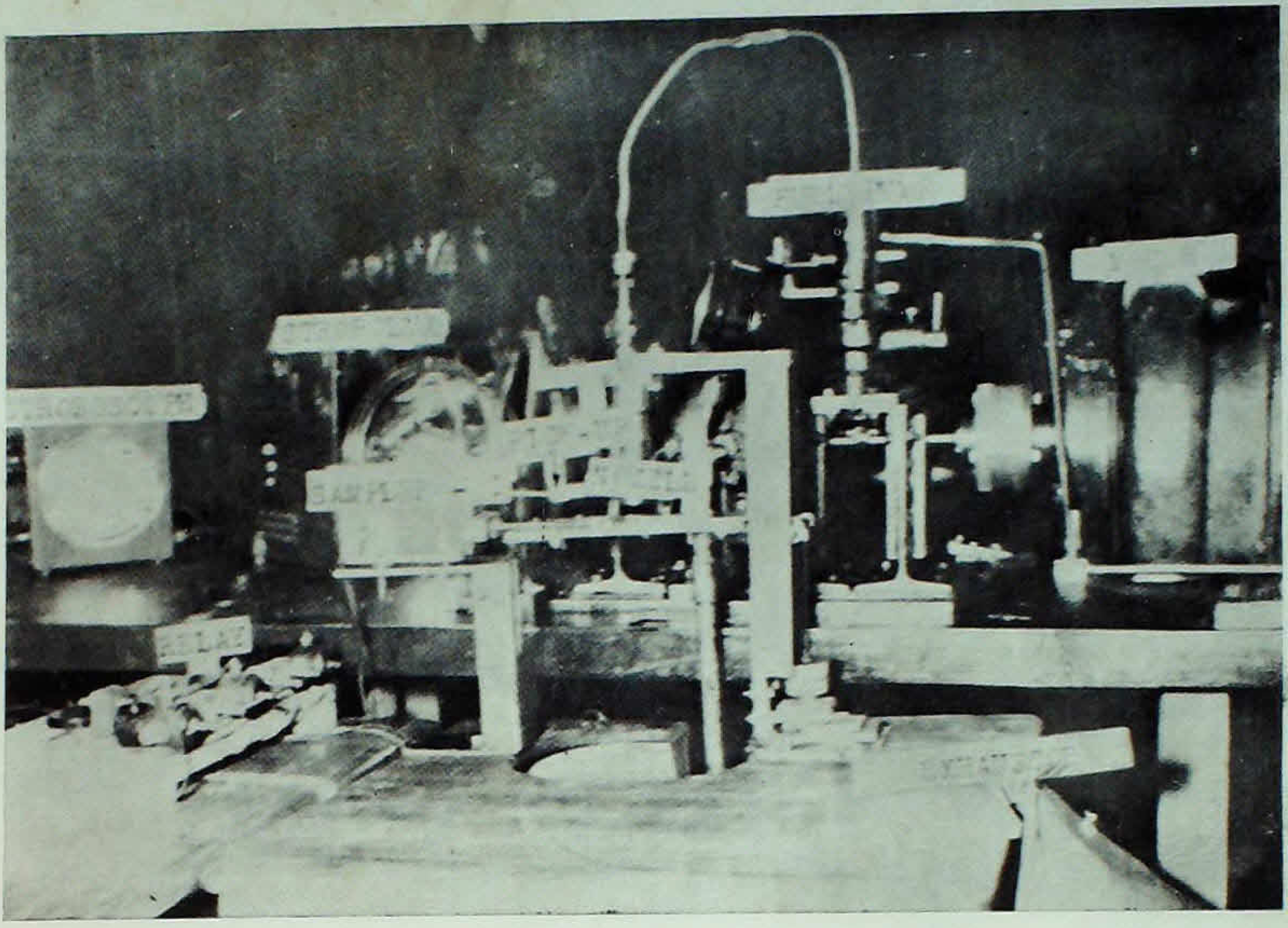
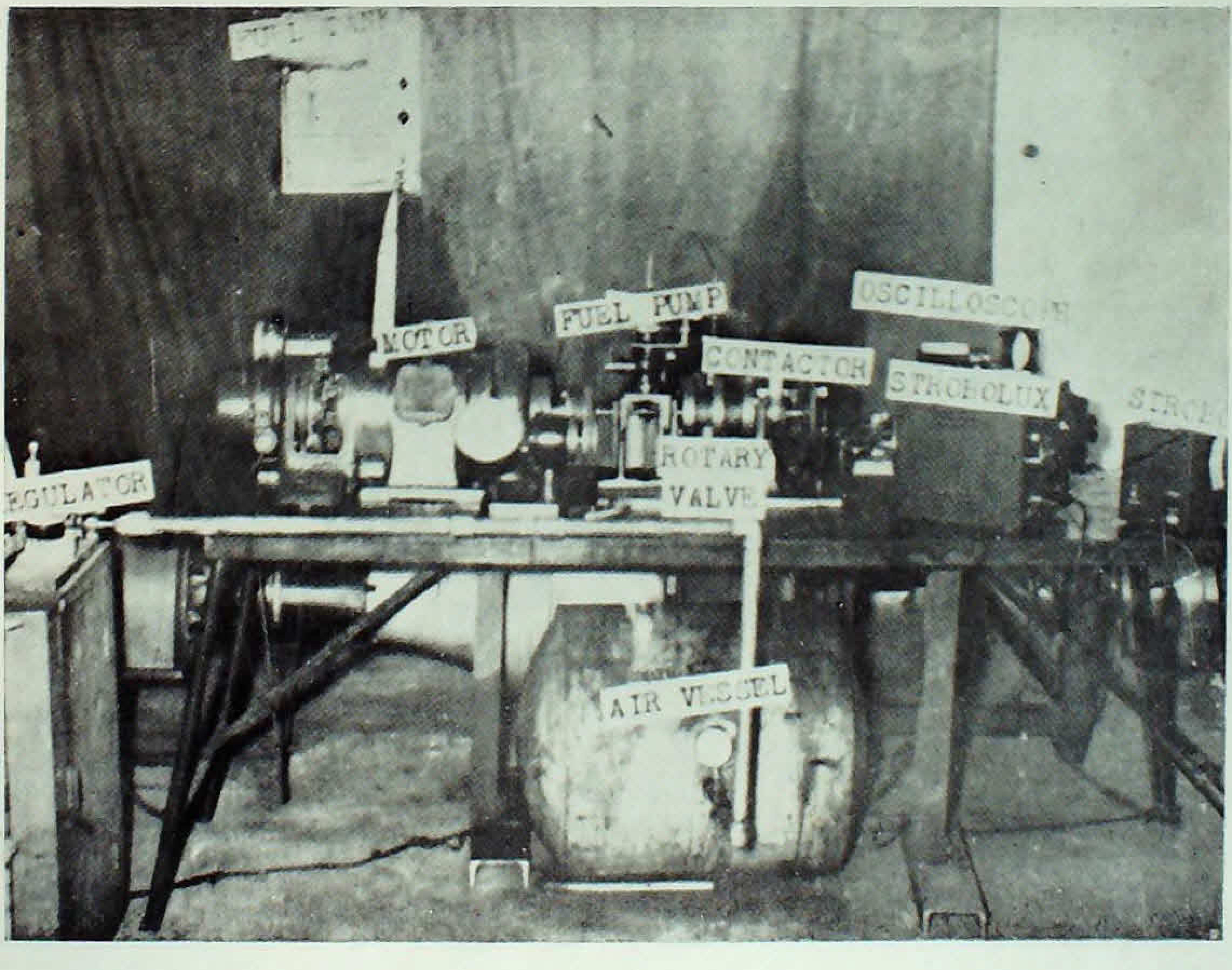


FIG. 19
Effect of Air Velocity on Spray Cone Angle



Right Hand Side View



Left Hand Side View

FIG. 11

Photograph of Spray Test-Rig

noted. The relationship between penetration and time was then obtained from these values. Figs. 23-26 indicate that spray penetration increases with increase in volume of air and air velocity and decreases as the nozzle diameter increases. The fuel orifice diameter appears to have no effect on penetration.

Mean Droplet Size. The effect of air velocity and flow ratio on mean droplet size was determined by varying the air velocity from 365 to 985 f.ps., and the flow ratio from 500 to 10,000. The mean droplet size for the total spray was determined taking into account the volume of fuel in the three regions of uniform atomisation. Fig. 27 shows the apparatus used for collecting the spray in each of these regions.

The variation of droplet size with air velocity, and flow ratio is shown in Figs. 28, 29. With increasing velocity for all values of flow ratios the droplet size decreases. With flow ratios less than 4,000, droplet size decreases rapidly as the velocity increases. For flow ratios above 4,000 however, the effect of velocity is comparatively smaller. The effect of flow ratio is negligible when it reaches values beyond 5,000.

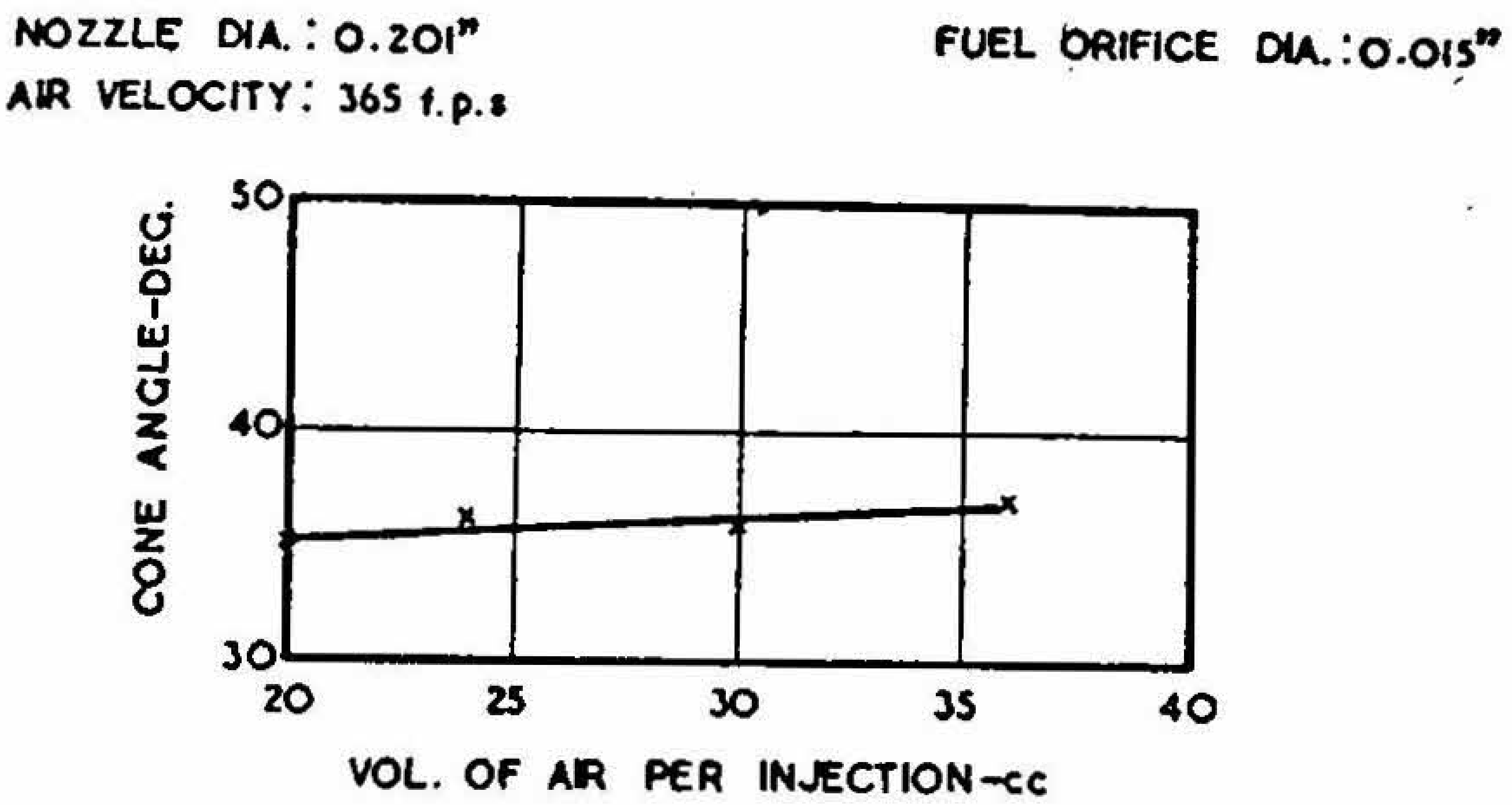


FIG. 20
Effect of Voıume of Air on Spray Cone Angle

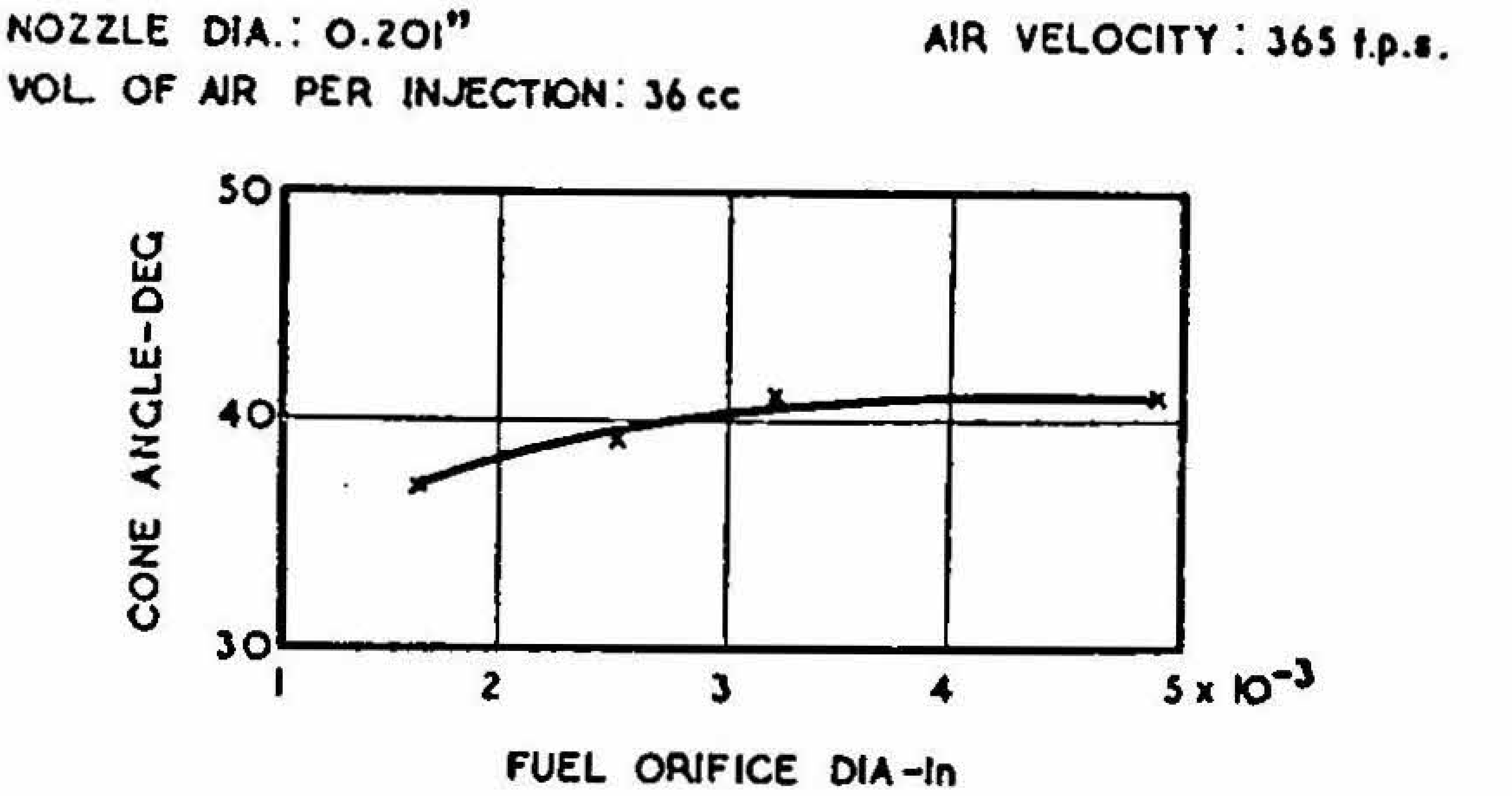


FIG. 21
Effect of Fuel Orifice Diameter on Spray Cone Angle

The effect of nozzle geometry on mean droplet size was investigated by varying the relative sizes of the fuel orifice and nozzle diameter. The fuel orifice diameter was maintained constant at 0.015 in., and the nozzle diameter was varied from 0.201 to 0.377 in. Fig. 30 shows the variation of droplet size as the nozzle diameter increases. Although the increase in droplet size for the limited range of nozzle diameters tried out during the experiments is small, the curve has a definite tendency to rise indicating poorer atomisation when the fuel orifice is disproportionately small compared to the nozzle diameter. The mean droplet size with a multi-hole nozzle (0.377 in., dia) in which four fuel orifices of 0.015 in., were so disposed as to obtain good intermixing of fuel and air is shown in Fig. 31. Comparison of Figs. 30 and 31 shows that for the same flow ratio and air velocity, the mean droplet size with the multihole nozzle is lower than that obtained with a nozzle diameter of 0.377 in., and a single fuel orifice of 0.015 in., diameter.

Spray Formation and Development: The formation of the spray over the injection period was obtained from photographs taken at different instants during separate injections under steady running conditions. Photographs in Fig. 32 are typical in illustrating the formation of the spray.

The spray is regarded as fully developed when the mean droplet size of the spray reaches its final value. The development of the spray was studied,

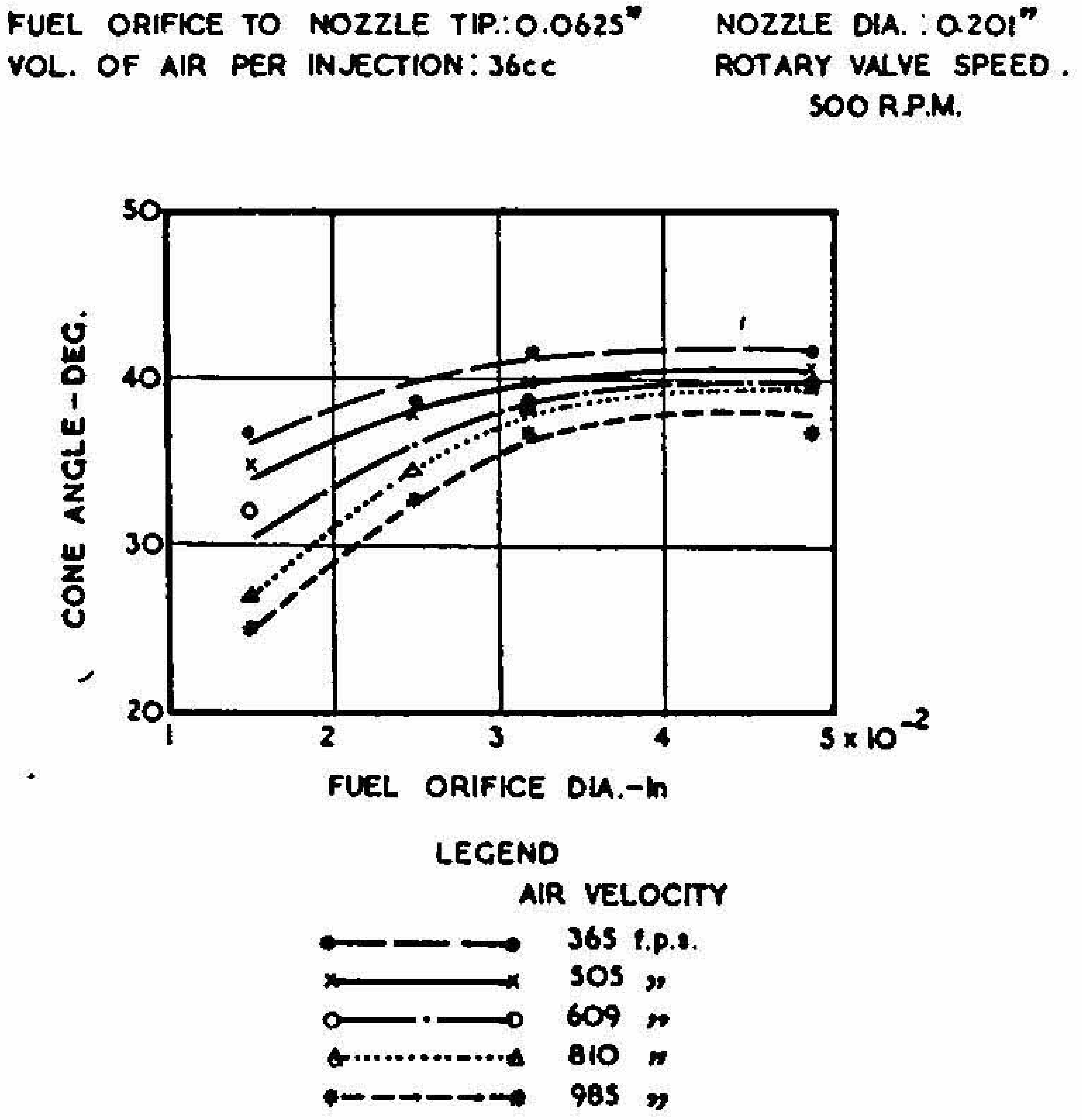


FIG. 22

Effect of Air Velocity and Fuel Orifice Diameter on Spray Cone Angle by measuring the mean droplet size of the spray over the period of injection, at different distances from the nozzle tip. Sampler II was used for collecting spray samples to measure the droplet size since it permits separation of a part of the spray at any point, without disturbing the spray itself very much. The nearest point where repetitive sampling could be obtained was about three inches from the nozzle tip. The central part of the spray being the coarsest, samples were collected at the centre, presuming that this would show up to better effect the variation in droplet size with distance from the nozzle. Fig. 33 shows the variation of droplet size with increasing distance from the nozzle.

DISCUSSION OF RESULTS

The results confirm, as expected, that the conclusions of Nukiyama and Tanasawa on the the effect of air velocity and flow ratio on mean droplet size in a continuous spray process, hold good for intermittent sprays as well. Further, it was observed that the nozzle geometry also plays a part in the effective use of the air supplied for atomisation. The results obtained are briefly discussed below.

Spray Cone Angle and Penetration. It is to be expected that in airblast sprays the cone angle and penetration would be closely related to the shape and penetration of the air blast itself; the penetration of the airblast being a function of its momentum. This is confirmed by the results obtained (Figs. 18 – 21 and 23 – 26). The decrease in spray penetration as the nozzle diameter is increased, may be attributed to the increase in air resistance from an increase in the diameter of the air jet issuing from the nozzle. The orifice diameter and air velocity are the only two variables that affect the spray cone angle (Fig. 22). At any air velocity as the orifice diameter increased the cone angle increases upto a maximum value and remains constant thereafter. The apparent dependence of spray cone angle on the orifice diameter, observed in Figure 19 may be explained as follows : the observed cone angle indicates the distribution of the disintegrated droplets within the envelope of the airblast. When the droplets are distributed over the entire volume of the air blast, the cone angle is a maximum and equal to the cone of the air blast. The observed cone angle may be taken to reflect therefore, how effectively the fuel and air are mixed at the nozzle.

Mean Droplet Size. It is observed from Fig. 28 that as the air velocity increases the droplet size rapidly decrases, although beyond a value of 700 f.p.s., the decrease in droplet size is less appreciable. Fig. 29 indicates that increasing the flow ratio improves mean droplet size. At any air velocity the effect of flow ratio appears to diminish after a particular limit. At low air velocities of the order of 365 to 505 f.p.s. it is found that the effect of flow ratio practically ceases beyond a value of 5000. At high air velocities its effect is less appreciable being negligible beyond a value of 1000 at an air velocity of 985 f.p.s.

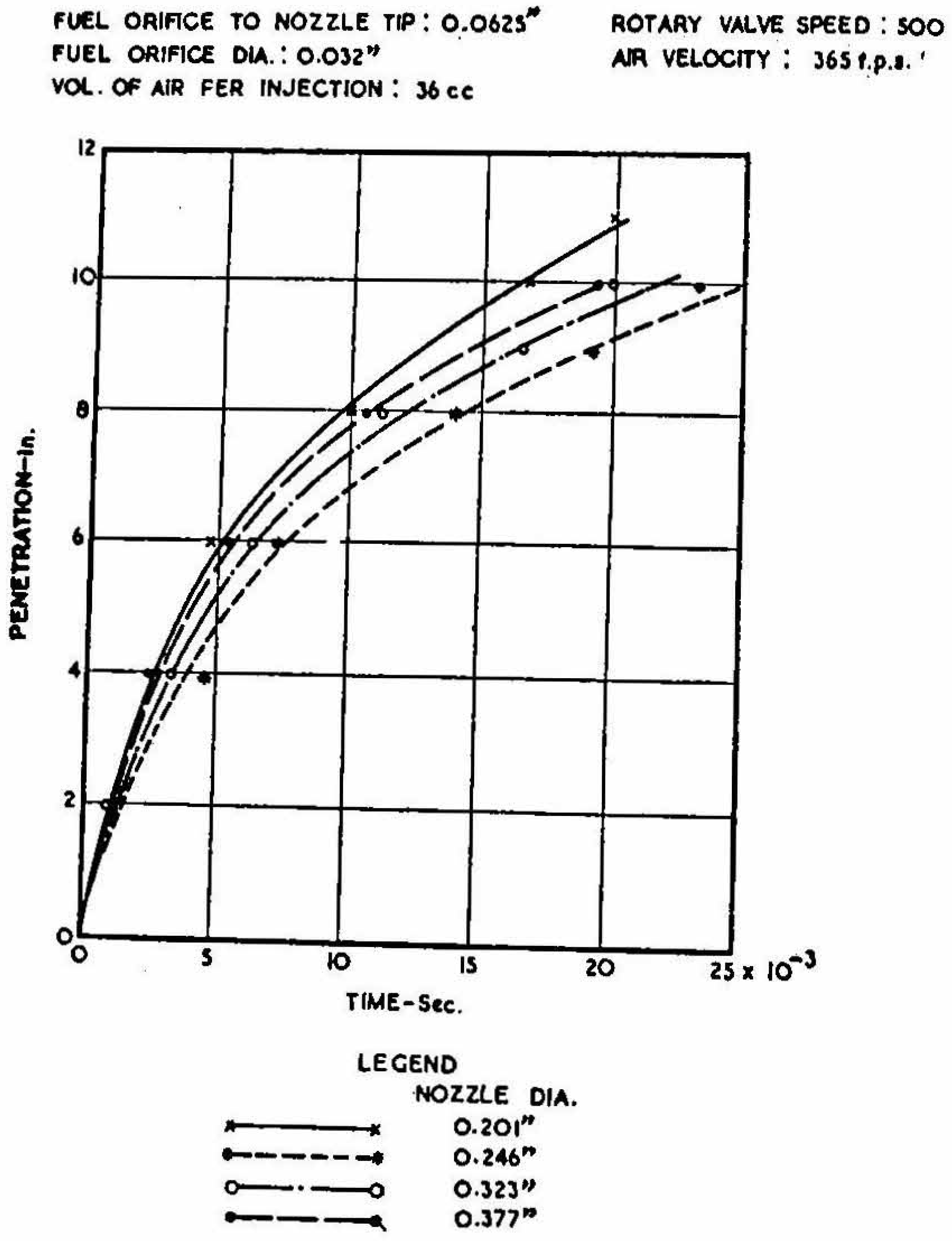


FIG. 23

Effect of Nozzle Diameter on Spray Penetration

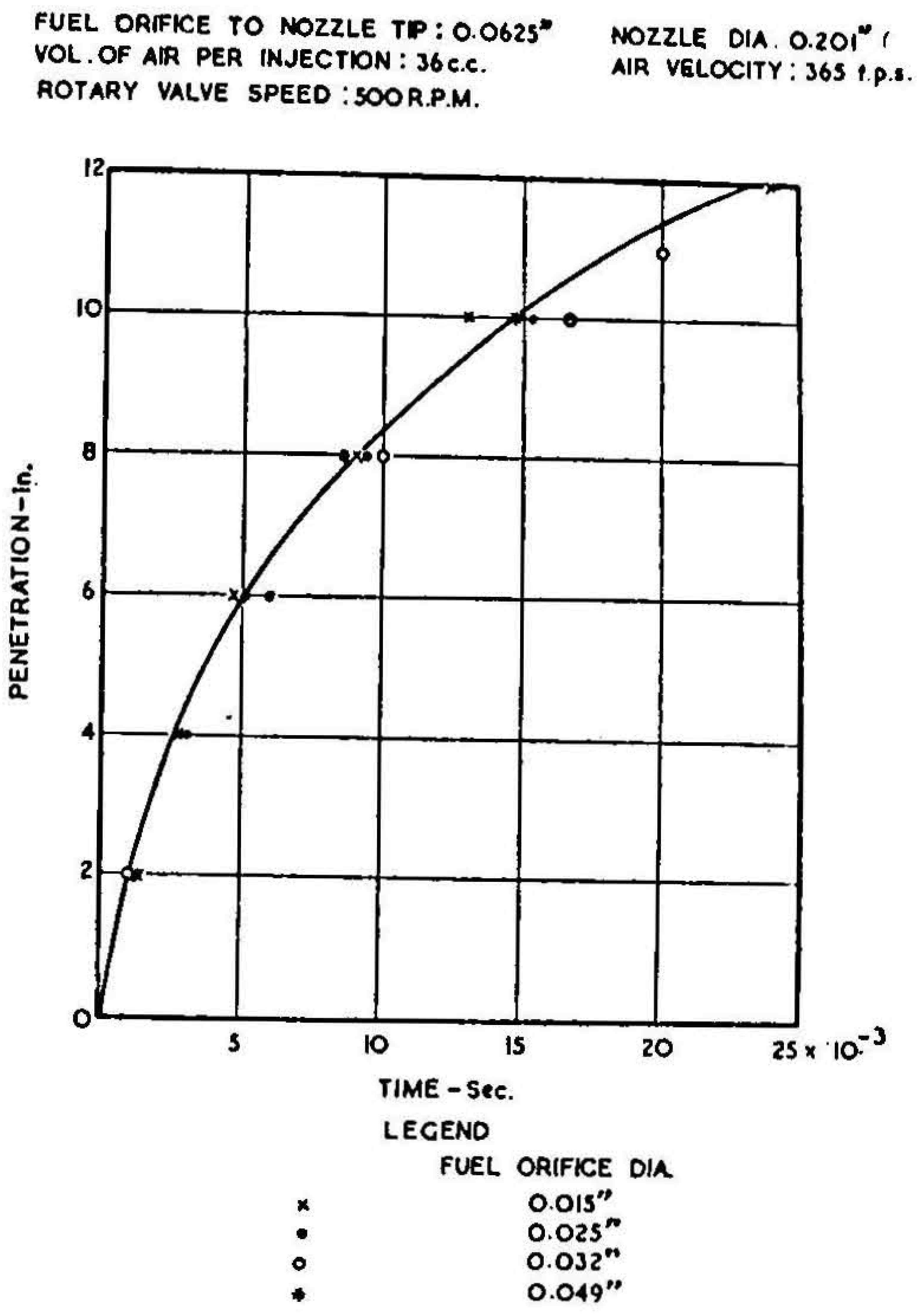


FIG. 24

Effect of Fuel Orifice Diameter on Spray Penetration

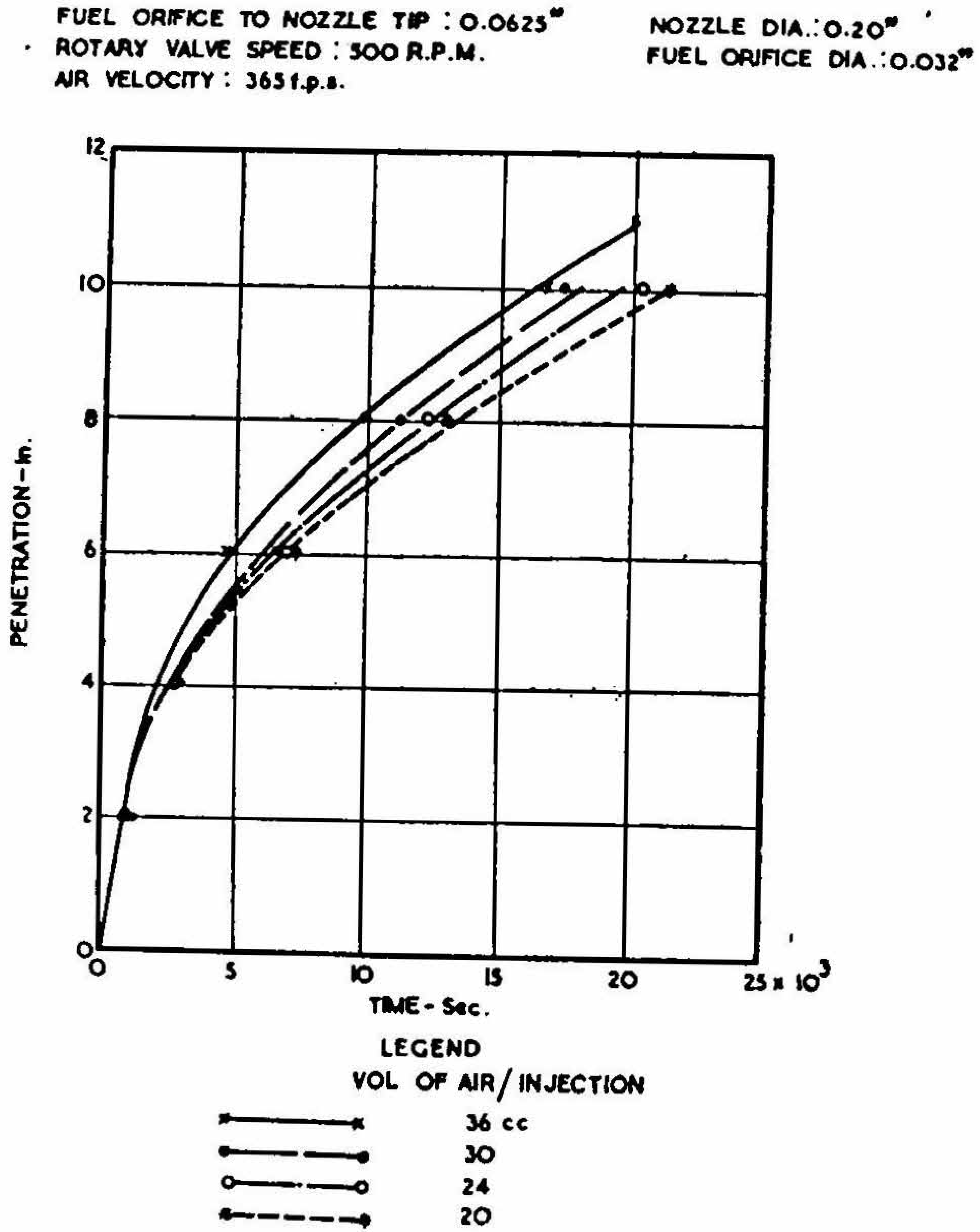


FIG. 25

Effect of Volume of Air on Spray Penetration

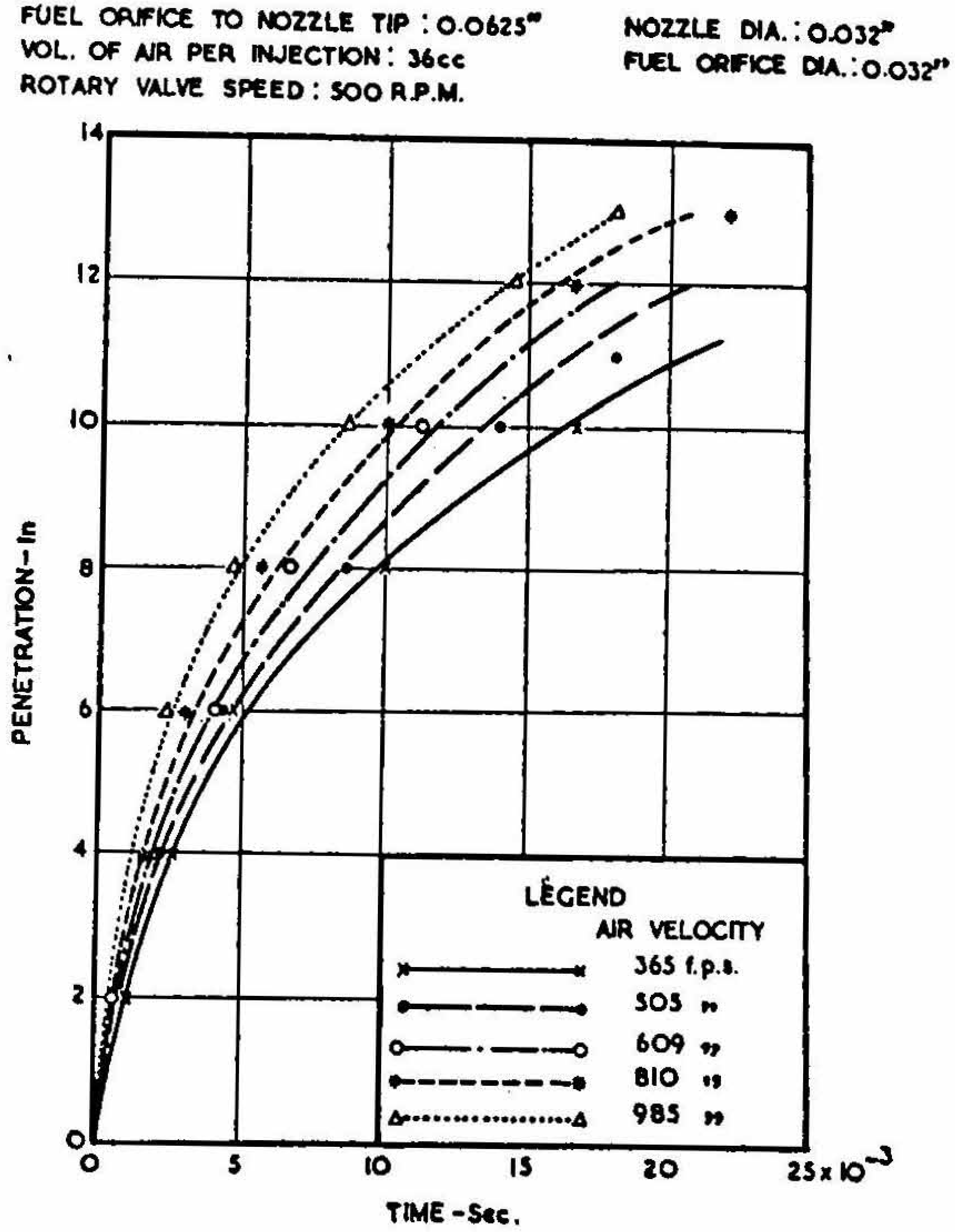


FIG. 26

Effect of Air Velocity on Spray Penetration

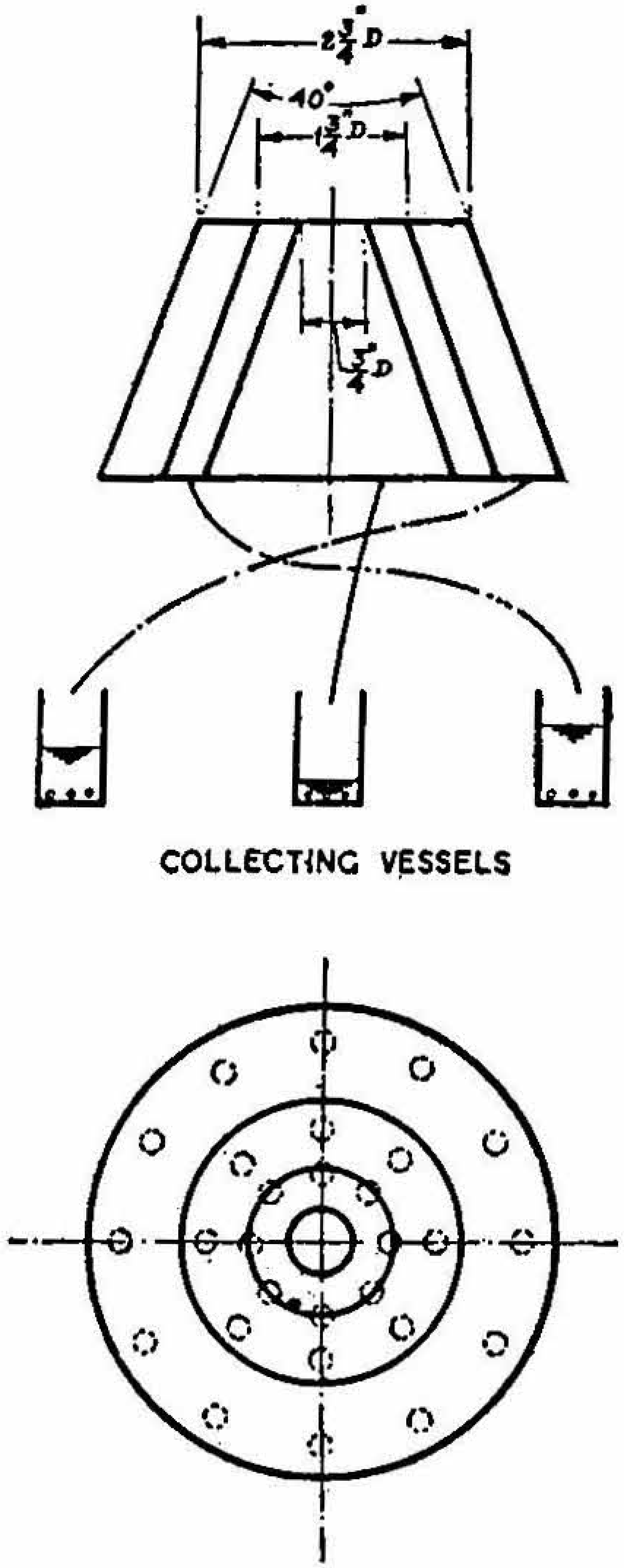


FIG. 27

Apparatus for Measuring Volume of Fuel in the three Regions of uniform Atomisation of the Spray

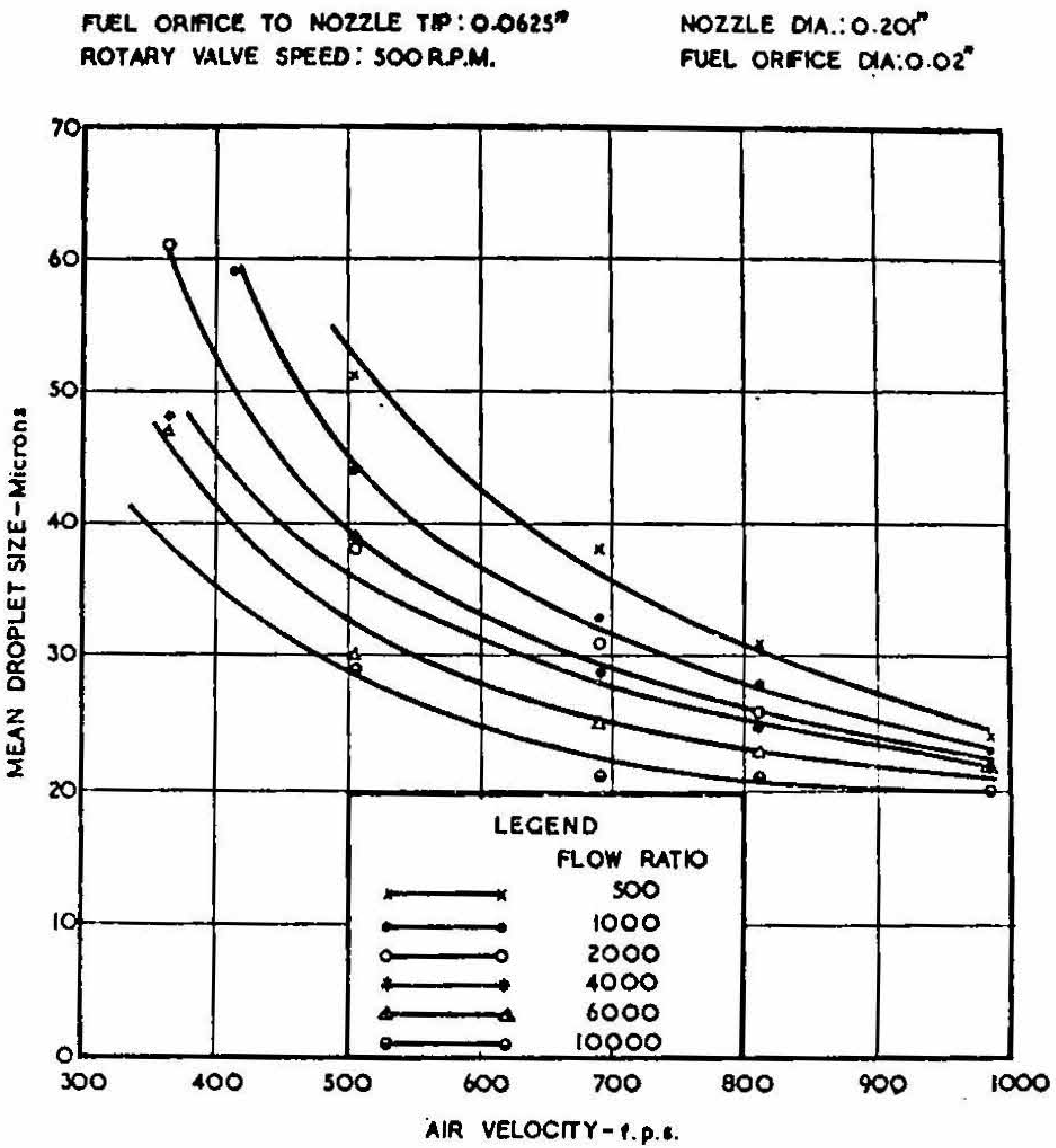


FIG. 28

Effect of Air Velocity on mean Droplet Size

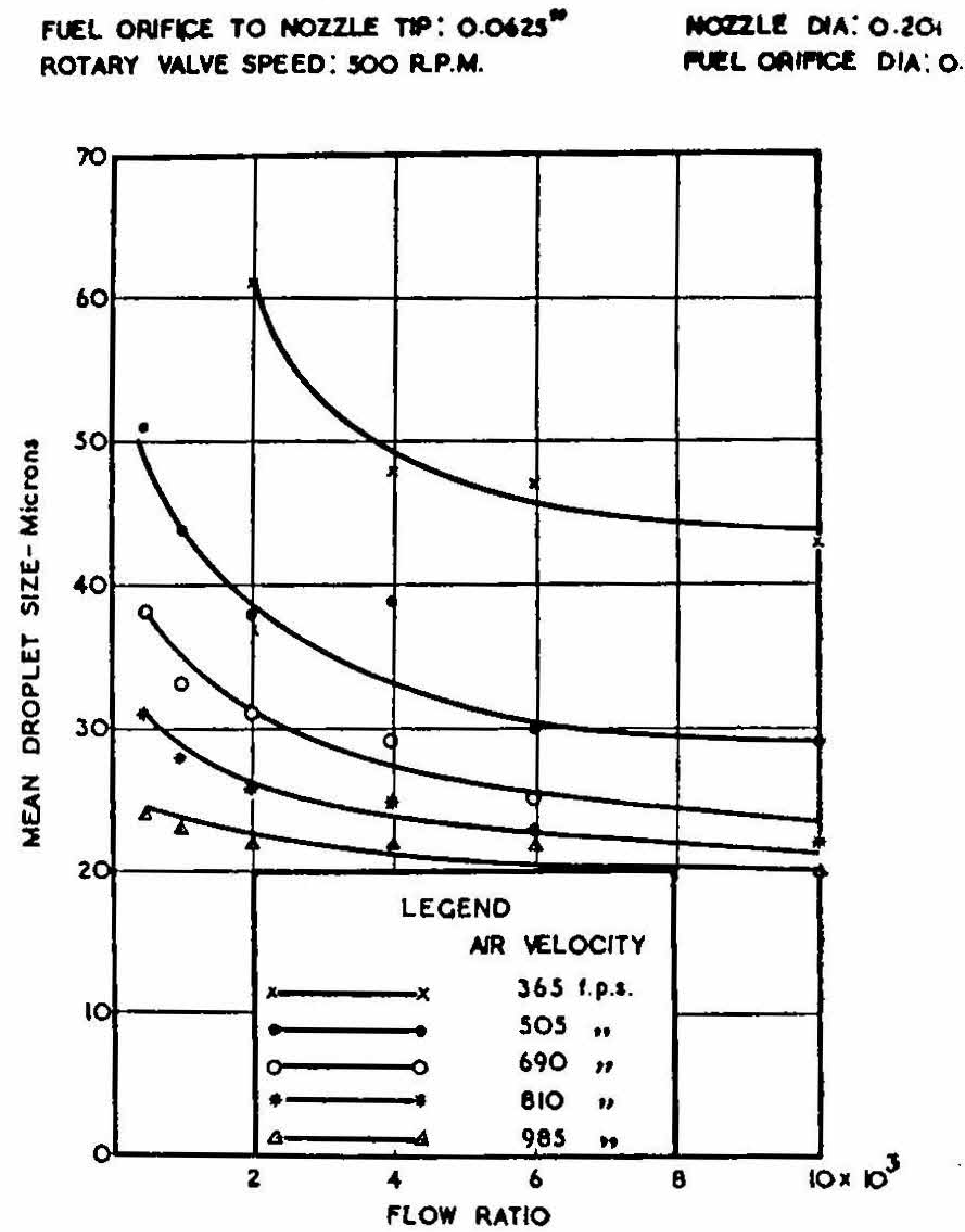


Fig. 29

Effect of Flow Ratio on mean Droplet Size

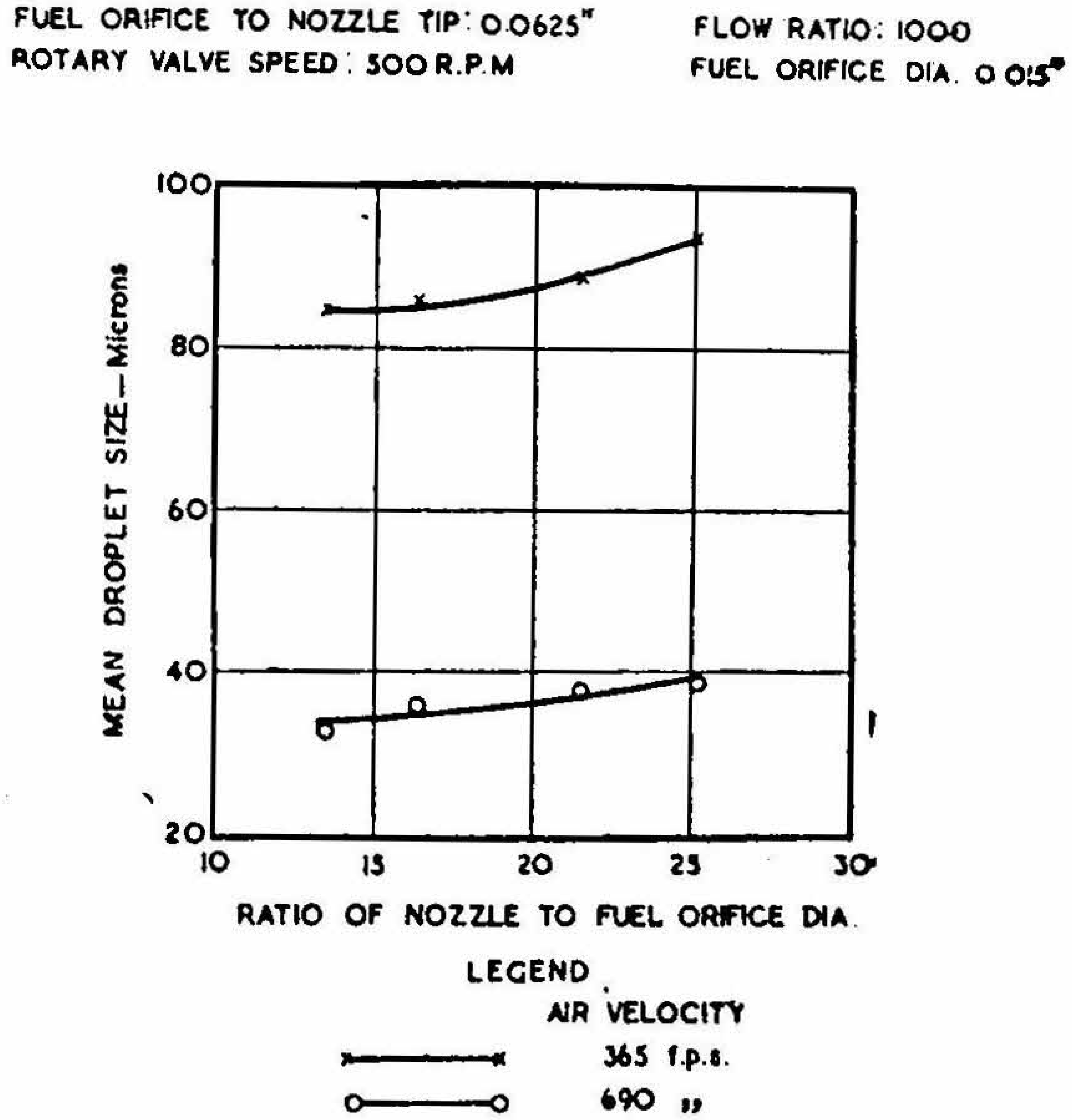


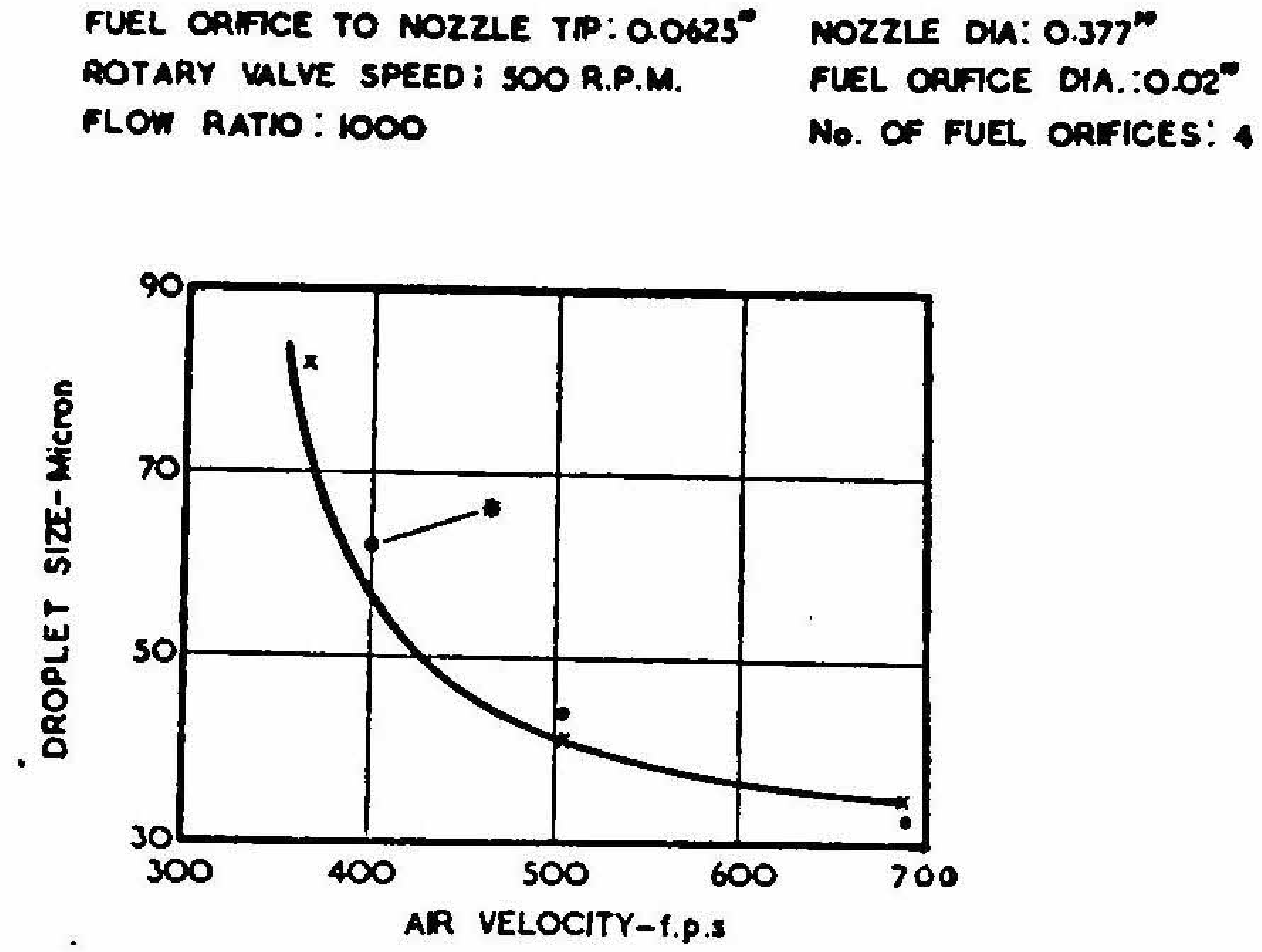
Fig. 30

Effect of Relative Size of Fuel Orifice and Nozzle Diameter on mean droplet size

It may be observed from Table 2 that for a given air velocity the spray intensity decreases as flow ratio increases. This is accompanied by a reduction in droplet size also. It would appear that one of the effects of increasing the flow ratio is to improve dispersion of the droplets within the spray thereby reducing the chances of coalescence among them. The resulting spray could therefore be expected to have finer droplets. Further it could also be expected that when the flow ratio has reached a stage when the droplets have been sufficiently well dispersed, any further increase in flow ratio would no longer affect the droplet size.

TABLE 2

Sl. No.	Air velocity	Flow ratio	Volume of fuel as percentage of total fuel			Average SMD
			Central region	Intermediate region	Outer region	
1	690 f.p.s (211 m/sec)	500	19	55	26	38
2		1000	17	56	27	33
3		2000	16	55	29	31
4		4000	16	55	29	25
5		6000	15	57	30	21
6		10000	13	57	30	21
7	810 f.p.s. (247 m/sec)	500	20	56	24	31
8		1000	19	57	24	28
9		2000	17	56	27	26
10		4000	16	57	27	25
11		6000	15	57	28	23
12		10000	15	57	28	21
13	985 f.p.s. (300 m/sec)	500	22	57	21	24
14		1000	20	58	22	23
15		2000	18	58	24	22
16		4000	17	58	25	22
17		6000	17	58	25	22
18		10000	85	59	26	19



Points taken from Fig. 28 corresponding to a flow
;Ratio of 1000

FIG. 31

Effect of Air Velocity on Mean Droplet Size. Multi-Hole Nozzle

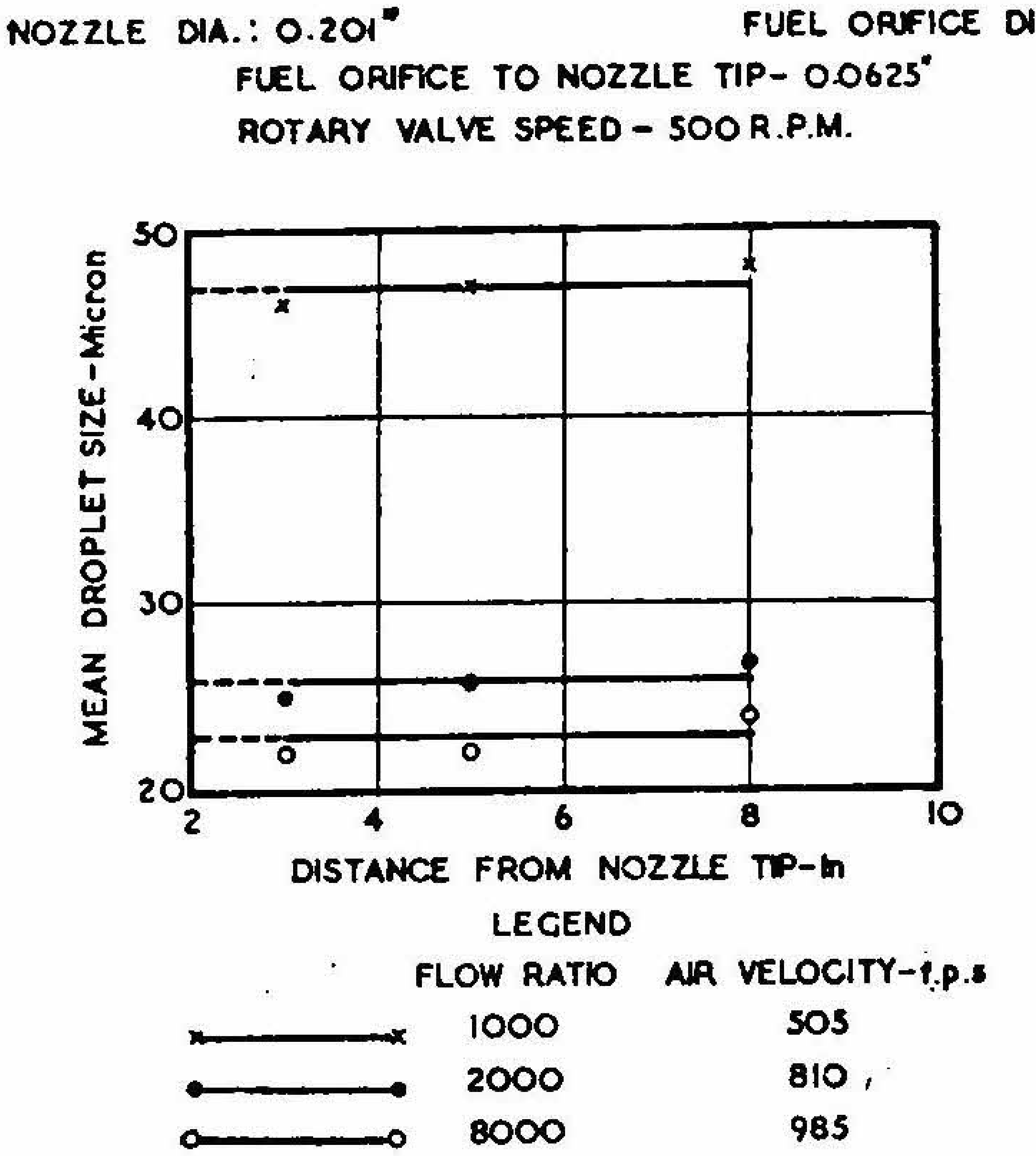


FIG. 34

Spray Development

The results of the experiments on the effect of nozzle geometry, particularly regarding the relative sizes of fuel orifice and nozzel diameters, indicate that the degree of atomisation deteriorates when the size of the fuel orifice is very small relative to the nozzle diameter.

As already noted while discussing the effect of fuel orifice size on the spray cone angle, when the fuel orifice diameter is very small compared to the nozzle diameter, the intermingling between fuel and air is affected. The air in the outer portion of the air blast being unable to take part in the atomisation process, the quality of atomisation suffers. This is confirmed by the results obtained (Fig. 31) with a multihole nozzle in which the fuel orifices were properly disposed to effect better mixing of fuel and air.

Hence for optimum results under given flow conditions it is necessary that the design of the nozzle should be such as to ensure good intermingling between fuel and air at the point where the relative velocity between air and fuel is maximum.

Spray Development. Because of the high velocity and intensity of the spray at points less than 3 in, from the nozzle tip, it was difficult to obtain representative samples in this region and values of mean droplet size obtained were erratic. Beyond this limit, however, the mean droplet size is substantially constant (Figure 33) indicating that the disintegration of the fuel is practically complete within a short distance from the nozzle. That is, the development of the spray is complete very near the nozzle. Theoretical analysis of the disintegration process also indicates that this should be so.

The several forces causing deformation and disintegration of liquid droplets moving in a gaseous medium are, the external gas resistance forces and the internal forces determined by surface tension and viscosity. Klusener[5] in an analysis of the disintegration of liquid droplets moving in a gaseous medium has shown that the air resistance plays an important part in the disintegration process. The air resistance depends on the velocity of the droplet relative to air and on the properties of air such as density and viscosity. Considering the balance between the normal air forces and surface tension, Hinze[6] has analyzed mathematically the effect of liquid viscosity on splitting of droplets. He has shown that a droplet splits if the ratio of air resistance pressure to the surface tension pressure is greater than a critical value. Nearest to the nozzle the value of this ratio, called ' Weber Number ', is highest.

The magnitude of the forces promoting disintegration of the fuel is therefore highest, in the vicinity of the nozzle. The fuel jet when subjected to these conditions should collapse and disintegrate into small droplets of such size that the surface tension pressure of the droplets is large enough to resist the external forces. The logical conclusion from this would be that atomisation of the fuel should be complete at the nozzle tip. However, the volume within which the entire fuel is enclosed as it issues as a spray from the nozzle is so small, that the effect of the phenomenon of coalescence of droplets as they collide among themselves is very important. Thus for a short distance in the immediate vicinity of the nozzle, coalescence and disintegration may be expected to be taking place simultaneously. Beyond this limit the droplets are distributed over a greater area and the chances of collision are reduced. Since the relative air velocity also decreases progressively both the coalescing and disintegration processes tend to become weaker and the disintegrated droplets are merely carried along by the air stream without any further change in their size. Similar results obtained by Nukiyama and Tanasawa on the development of an airblast spray, also lend support to this view.

CONCLUSIONS

The following conclusions can be drawn from the investigation.

(1) Spray cone angle is independent of the volume of air used for atomisation. It is affected slightly by the air velocity.

(2) Spray penetration decreases with increase in nozzle diameter and increases with increase in air velocity and volume of air. Fuel orifice diameter has no effect on spray penetration.

(3) The development of the spray is complete within a short distance from the nozzle.

(4) Mean droplet size decreases as flow is increased. However, its effect ceases beyond a particular limit, at any air velocity. The limiting value of flow ratio varies from about 5000 to 1000 for air velocities ranging from 365 to 985 f.p.s.

(5) Air velocity appears to have the greatest effect on the degree of atomisation. Mean droplet size decreases rapidly as air velocity increases. Beyond a value of 700 f.p.s., however, the decrease in droplet size for an increase in air velocity is less appreciable.

(6) The design of the nozzle should ensure good intermingling between fuel and air, at the point where the relative velocity between air and fuel is maximum, for the full use of the air supplied for atomisation.

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